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Applied Research Laboratory

Report on the 1999 ONR Shallow-Water Reverberation Focus Workshop

J.R. Preston

With assistance from group leaders:
Roger Gauss and Dajun Tang

and panel members:

Peter Cable
Warren Denner
Eugene Dorfman
Dale Ellis
William Hodgkiss
Charles Holland
Anatoliy Ivakin
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Nick Makris
Robert Odom
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Mike Sundvik
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Ji-Xun Zhou

Technical Memorandum
File No. 99-155
31 December 1999

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REPORT ON THE 1999 ONR SHALLOW-WATER REVERBERATION FOCUS WORKSHOP

J. R. Preston	ARL/PSU

With assistance from group leaders:

Roger Gauss	NRL
Dajun Tang	APL/UW

and panel members:

Peter Cable	BBN/GTE
Charles Holland	SACLANTCEN
David Knobles	ARL/UT
Nick Makris	Massachusetts Inst. of Technology
Robert Odom	APL/UW
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Abstract: The Office of Naval Research Ocean Acoustics Program held a Shallow-Water Reverberation Focus Workshop on August 25, 26, and 27, 1999 in Santa Fe, New Mexico. The primary objective of the workshop was to convene a small group of leading scientists in the area of acoustic reverberation to identify current scientific issues relating to shallow-water reverberation, scattering mechanisms, and associated reverberation experiments. The key focus was on bottom reverberation and bottom scattering. In particular, The workshop emphasis was on the definition of goals for current and future ONR shallow-water reverberation projects, and issues related to the development of reverberation models and experimental designs. The frequency range of interest for this workshop was for the band from ~ 50 Hz – 6 kHz. The upcoming US Asia experiment was an important topic of discussion during the latter part of the workshop. This report is a summary of the findings and deliberations of that meeting. It includes a list of key unanswered questions relating to sea floor reverberation and scattering.

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ACKNOWLEDGEMENTS

As moderator of this workshop, I would like to thank several people for their efforts, cooperation, and goodwill for without them the Shallow-Water Reverberation Focus Workshop would not have been possible. Thanks to Dr. Ellen Livingston for giving me the opportunity to serve as moderator and for all her hard work in making it a success. Secondly, much appreciation is due to the two group leaders, Drs. Roger Gauss and Dajun Tang for their great jobs in leading the panels and ultimately providing the summaries of their group's deliberations. Special thanks to Ms. Bev Kuhn who took care of much of the paperwork, logistics, and countless other details involved in organizing this meeting. Thanks to Drs. Jeff Simmen and Eddie Estalote of ONR for their support and participation in this effort. Finally, all the workshop participants deserve special thanks for making the meeting a success and for helping with the editing of this report.

LIST OF FIGURES

I. INTRODUCTION

The study of reverberation is well known to be a very complex one with many competing mechanisms seen in real data (see Fig. 1). Much progress has been made in our understanding of reverberation (see for example ONR sponsored Acoustic Reverberation Special Research Program (ARSRP) and Critical Sea Test (CST) program publication lists and the abstracts and reference list for this workshop). However, there remain important unanswered questions and a real scarcity of high-quality basic research data sets. For example, Fig. 2 shows the large spread in some typical shallow water bottom scattering strength estimates but in most cases not enough supporting measurements were taken to rule out competing mechanisms like surface or volume scattering at low grazing angles.

To address this important problem, the ONR Ocean Acoustics Program held a Shallow-Water Reverberation Focus Workshop on August 25, 26, and 27, 1999 in Santa Fe, New Mexico. The primary objective of the workshop was to convene a small group of leading scientists in the area of acoustic reverberation to identify current scientific issues related to shallow-water reverberation, scattering mechanisms, and associated reverberation experiments. The key focus was on bottom reverberation and bottom scattering. In particular, the workshop emphasis was on the definition of goals for current and future ONR shallow-water reverberation projects and issues related to the development of reverberation models and experimental designs. The frequency range of interest for this workshop was for the band from ~ 50 Hz – 6 kHz. The upcoming US-Asia experiment was an important topic of discussion during the latter part of the workshop.

The meeting consisted of a day of technical presentations followed by a day and a half of discussions on reverberation and scattering experiments (led by R. Gauss) and on reverberation modeling recommendations (led by D. J. Tang).

The workshop was split into two working groups on the afternoon of the second day to develop recommendations for ONR. On the third day the two groups' deliberations were presented and discussed. Sections II through V are an attempt to reproduce the working groups' conclusions but have been reorganized and modified for readability and edited by the entire group to refine its recommendations. Section III contains the unresolved scientific questions (hypotheses) that the group considered most important. Sections IV and V contain planning information to implement the experimental and modeling groups' recommendations. An interesting observation from the Shallow-Water Acoustic (transmission loss) Modeling workshop - SWAM99, is included in Section V. A summary of workshop highlights for ONR is presented in Section VI. A list of available experimental assets is given in Appendix A. Appendix B lists some current reverberation models. The meeting agenda is included in Appendix C. The workshop abstracts are included as Appendix D and Workshop attendees and contact information is included as Appendix E. Finally, some relevant references are included at the end of this report as Appendix F and as a supplement from Defence Research Establishment Atlantic (DREA) in Canada.

Background - I

Complexity of Reverberation

Reverberation in shallow water can be due to a combination of bottom, volume and surface scattering, the relative influence of which depends on both waveguide and sonar-system characteristics

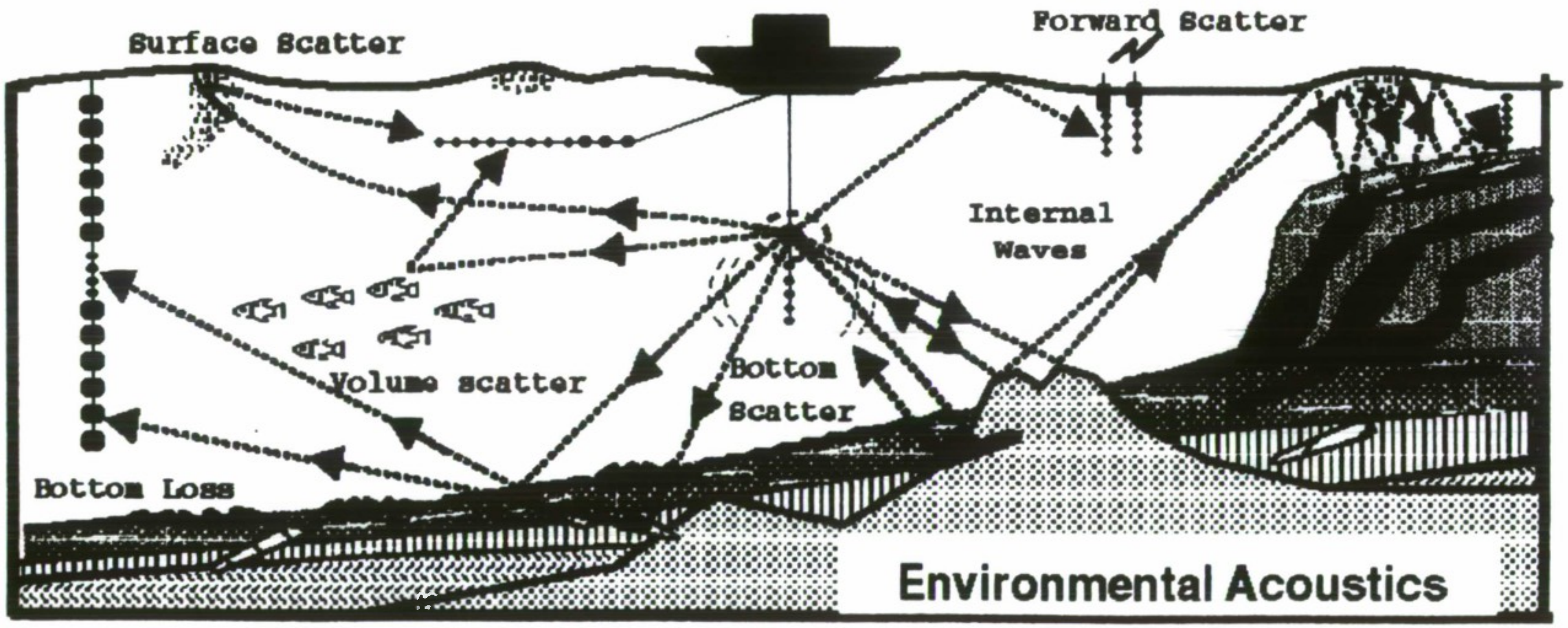


Figure 1. The complexity of reverberation measurements. Courtesy of R. Gauss.

Background - IV

Acoustic Variability

Environmental Variability leads to Acoustic Variability

Example:

BOTTOM SCATTERING STRENGTHS

Mechanisms

Rough interfaces

Water-sediment

Sediment-sediment

Sediment-basement

Sediment volume

What are their relative contributions?

What is the role of fish?

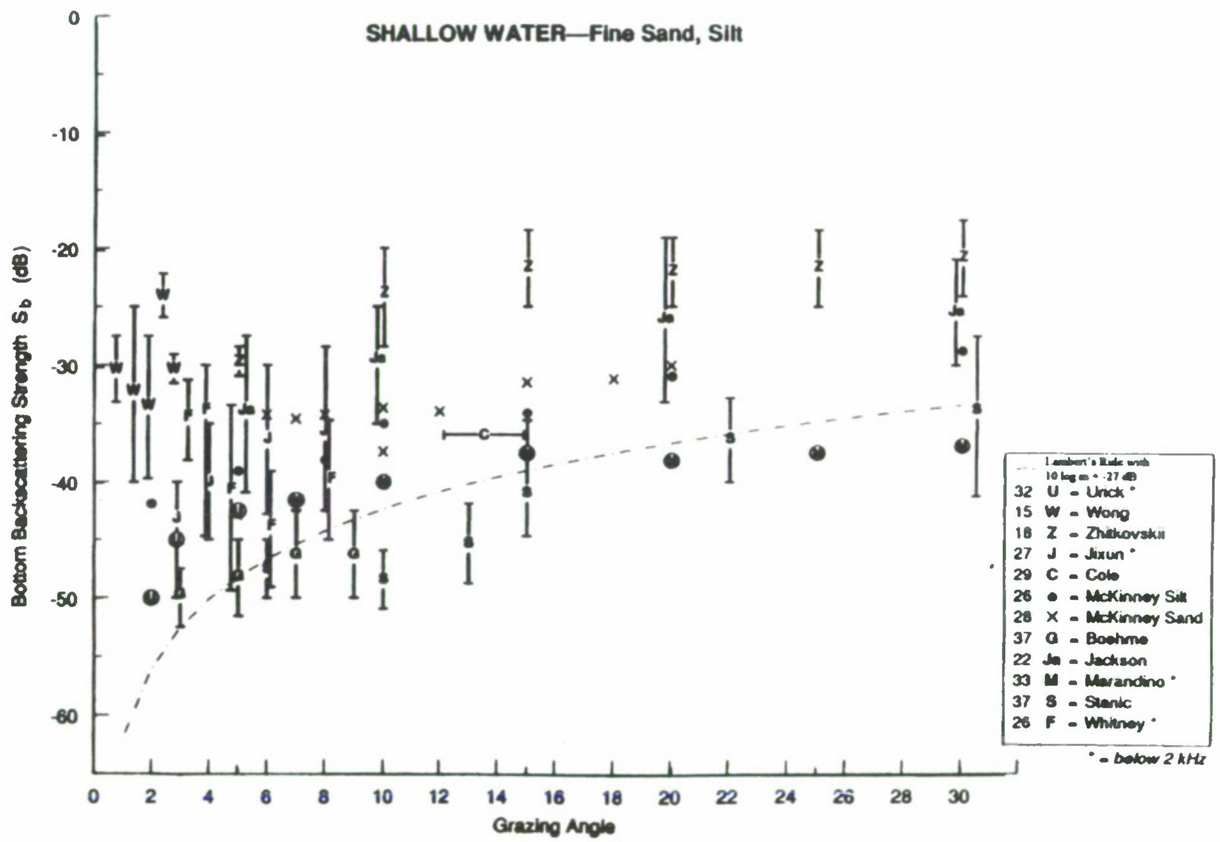


Figure 2. Illustration of the wide variation in measured shallow water scattering strengths. Courtesy of D. McCammon and R. Gauss.

Some Definitions:

Two interesting requests made by ONR at the meeting were for the group to define reverberation and to define clutter. The group consensus on a definition for reverberation was: any source related energy received by an acoustic sensor after signal generation onset that was not energy returned by a target (and in the bistatic case not the one-way received energy associated with a transmission loss measurement from source to receiver). This definition excludes ambient/background noise. The group consensus was to sidestep the issue of separately treating forward scatter as it relates to reverberation. Clutter was defined as that which comes through a sonar display that can be confused with a target or confound the classification process (therefore, it is dependent on the sonar system being used). For completeness, bottom scattering as used here refers to the very localized process of redirecting incident energy from a confined bottom or sub-bottom patch and does not include the specularly reflected portion of the redirected energy.

Implied in all the references to scattering and reverberation measurements below is the intention to quantify mean level quantities and associated statistical measures like variances. If possible, estimates of cumulative density functions (CDFs) and or probability density functions (PDFs) should also be made.

During the workshop some specific questions were posed by ONR, namely:

1. What are the deficiencies in current measurement techniques?
2. What needs to be measured and what resolution is required in these measurements?
3. What instruments are needed to get the geology and geophysics (G & G) data these experiments and modeling efforts will require?
4. What tools (including models) are needed to improve the geo-acoustic inversions?

Questions 1 - 3 are answered in Section IV A and question 4 is answered in Section V C where they fit into the appropriate topic areas.

II. GOALS AND STRATEGIES FOR IMPROVED UNDERSTANDING OF BOTTOM REVERBERATION AND SCATTERING

Scientific Goals:

- Design experiments to isolate the scattering and propagation mechanisms that are important factors in observed reverberation.

- Measure (and predict) scattering and reverberation on both local scales (direct path ranges) and regional scales (multipath ranges). On the local scales, characterize select scattering patches in great detail. On the regional scales, use reverberation data to verify/refine extrapolation methods from local to regional. These experimental efforts must collect high quality, high resolution, oceanographic, and geophysical supporting data.

- Validate and refine inverse measurement/model techniques (this requires attempts to obtain ground truth for inversions). We refer to inversion of both the one-way data and the reverberation data for geoacoustic parameters, but the reverberation data can also be inverted for scattering parameters.

Programmatic goals:

- Identify the technology base (assets) available to design and conduct experiments.

- Develop uniform measurement procedures that include environmental adaptation using reverberation data, one-way transmission loss (TL) data, and two-way down-looking chirp sonar data.

- Develop and apply new techniques to Rapid Environmental Assessment (REA), Environmentally Adaptive Sonar Technology (EAST), and similar programs. (Better physical models will give rise to EAST/REA improvements and in turn should lead to better and wider area assessments with feedback to modeling). Figure 3 shows an example by NUWC of rapid area inversion for the EAST program.

III. BOTTOM REVERBERATION AND SCATTERING QUESTIONS

The questions in this section are divided into those pertaining to the water-bottom interface, those pertaining to the sub-bottom, those pertaining to both, and those pertaining to neither. The following represent both the experimental and modeling group questions.

A. The water-bottom interface:
1. Does the water-bottom interface contribution dominate long-range bottom reverberation?
2. What questions remain concerning scattering from the water-bottom interface?
3. Are large bottom impedance contrasts and/or shear speed contrasts important to scattering? Or are they only a TL effect in the reverberation?
4. What is the relative importance of discrete vs. diffuse bottom scatterers?
5. When must the elastic/shear properties of the bottom be included when modeling reverberation?
6. How important are the larger scale (> 1 λ) bathymetric features to long-range reverberation?
7. Interface roughness models often assume transverse isotropy. Is this valid?

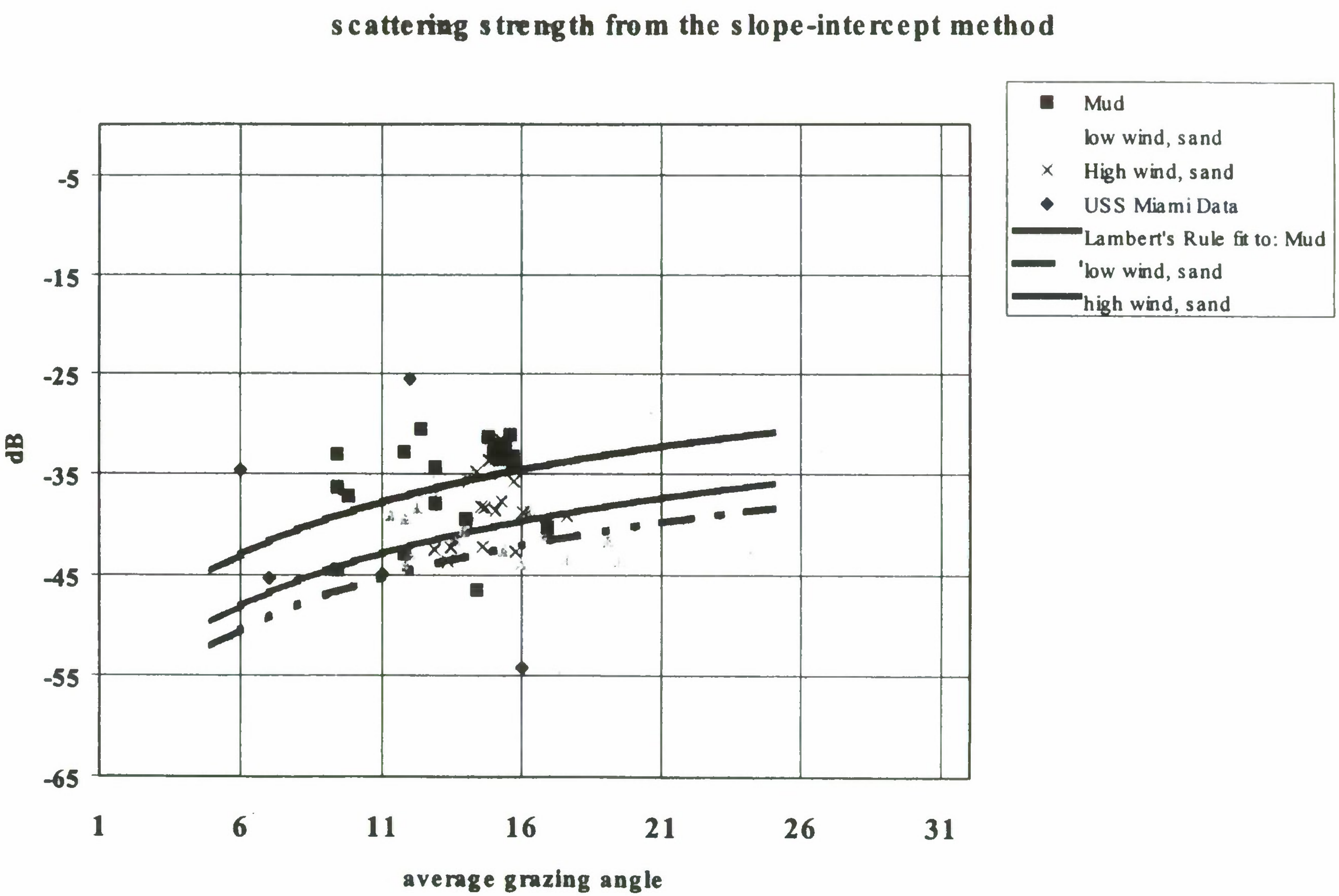


Figure 3. Example of shipboard inversion for scattering strengths vs. grazing angle for EAST program. Courtesy of M. Sundvik.

B. The sub-bottom:

1. Is sub-bottom layering important to long-range bottom reverberation?
2. What is the relative importance of fluctuations in the sediment properties, discrete sub-bottom features, and statistically rough sub-bottom horizons on scattering and reverberation?
3. How important are the large scale (> 10 λ) sub-bottom features to long-range reverberation?
4. How can we improve our ability to measure needed G & G parameters of the sub-bottom, in particular c_p, ρ, and α, and the associated gradients?
5. How can we measure/estimate the character of sub-bottom inhomogeneities in 3-D and how should they be parameterized in models?
6. Can long-range shallow-water reverberation from the sub-bottom be ruled out under some instances – if so what are they?
7. What drives the frequency dependence of scattering strengths when it is observed?

C. Both the water-bottom interface and the sub-bottom:

1. Is the critical angle effect (see Mourad–Jackson (1993) and Essen (1994), for example) actually seen in shallow-water reverberation data or does nature tend to smooth it out?
2. True or false: Interface scattering varies slowly and monotonically with frequency while sediment volume scattering varies non-monotonically with frequency (e.g. near Bragg frequencies)?
3. How important is sub-critical angle penetration for rough interfaces at low frequencies?
4. Can one use existing vertical line array (VLA) data to validate the separability of interface scattering?

D. Other questions:

1. Is clutter due to non-diffuse scattering?
2. How important is the sediment-basement interface roughness? How can we measure that roughness? What measurement can separate this mechanism from others?
3. How are the statistics of geophysical parameters affected by the measurement geometry and sensor resolution?
4. For what frequency ranges is reverberation from sandy sediments unaffected by the Biot slow wave in the bottom?
5. If gas hydrates are present, how do the sensitive phase changes with temperature affect reverberation?
6. Attenuation in sediments can be non-linear with frequency. See for example Fig. 4 from Zhou (1985, 1987). In these cases, why? What models can explain this? Buckingham has some theories (1997,1998); are they adequate? This question also will require broadband measurements.)
7. Is the depth dependence of sediment sound speed and attenuation as predicted by Hamilton a valid model, or are they better modeled by

Seabottom Attenuation from Inversion of Sound Propagation Data in the Yellow Sea

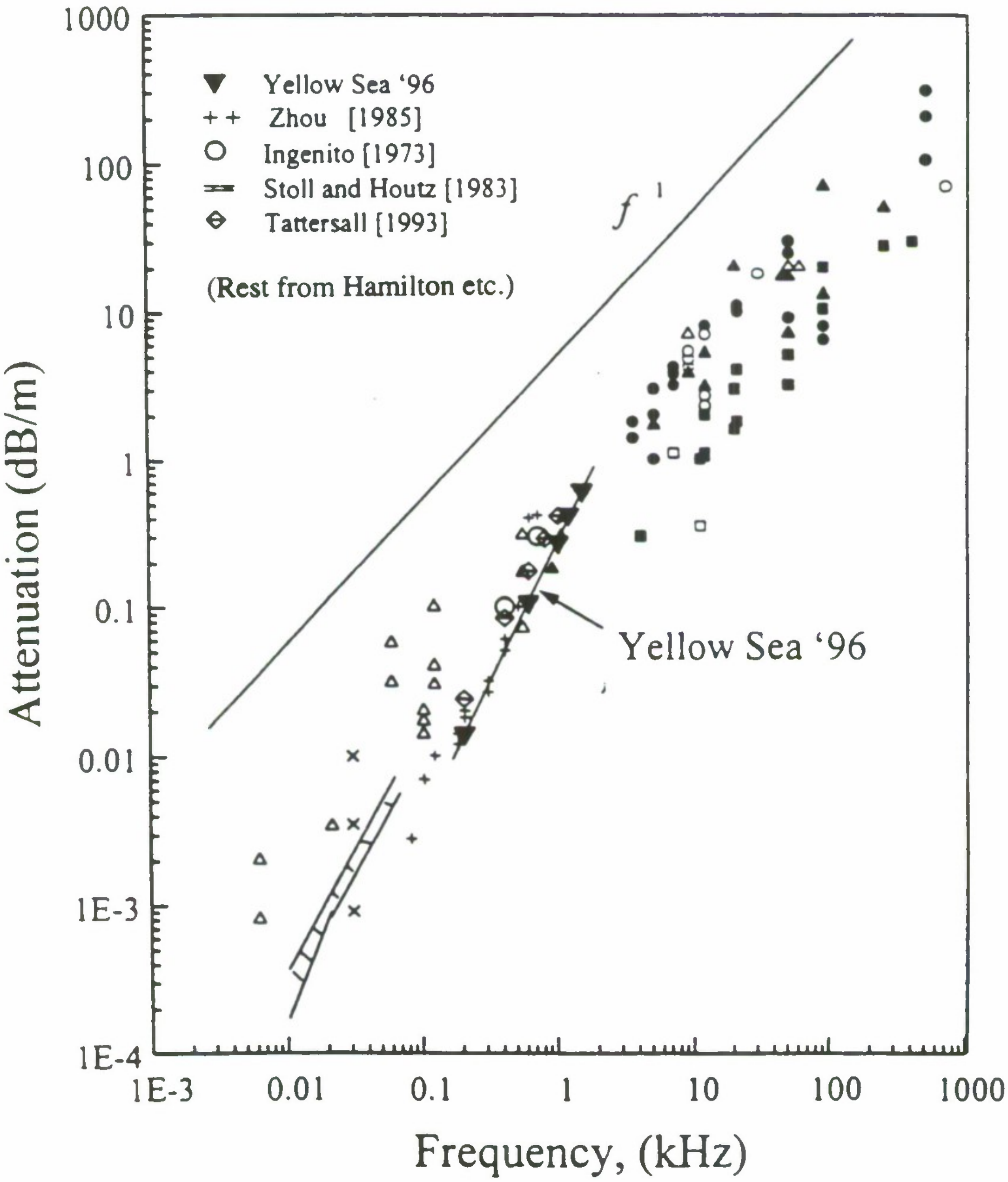


Figure 4. Yellow Sea data showing non-linear dependence of bottom attenuation vs. frequency. Courtesy of J. Zhou.

constant speed and attenuation layers as suggested by Gettrust et. al (1988) and Wood and Gettrust (2000), or are other models needed?

IV. SUMMARY OF THE WORKING GROUP FINDINGS - EXPERIMENTAL

A. Bottom Reverberation and Scattering Experiments – Some Background via Answers to ONR's First Three Questions:

ONR question 1: What are current acoustic measurement-technique deficiencies?

- Often, too few measurements (sparse and/or averaged data) are taken.
- Measurements are inadequate (for example, having insufficient resolution, range of dynamic variables, or having inadequate dynamic range).
- Measurements are incomplete, for example partial environmental ground truth or incomplete measurements of quantities needed to determine the dependency of bottom scattering on grazing angles.
- Isolation of direct path scattering is more difficult in range-dependent shallow-water areas.
- Inverse techniques to estimate a geo-acoustic model often lack consensus ground truth.
- Control of sensor geometry is poor relative to a wavelength or less (e.g. position, tilt, heading, etc.).
- Data processing often assumes scattering is from water-sediment interface, meaning estimates of scattering strength (SS) vs. grazing angle will be in error if untrue.
- Data processing often assumes scattering is plane-wave in nature, which may often be untrue.

ONR question 2: What needs to be measured and what resolution is required in these measurements?

Recommended Parameter Sample Intervals:

- Environmental parameters should be sampled approximately every 10 λ in range for propagation modeling. This is the rough rule of thumb for the Ram PE grid size in shallow water (see Ref. ** at the end of the reference section). The workshop group also chose the same sample spacing as constituting an ideal input data set in the absence of specific knowledge about a shallow water site. This sample interval could actually be much different depending on correlation length scales of key environmental parameters driving the propagation loss at a particular site.
- Environmental parameters should ideally be sampled or stochastically extrapolated down to approximately 0.2 λ in range and depth to model the scattering. (Since the Bragg components in backscatter range up to double the highest incident frequency, sampling at exactly Nyquist would give 0.25 λ spacing).

- Bottom parameters (density, sound speed etc.) should be sampled in depth down to at least to 2λ for fast (e.g. sand-like) bottoms and ~ 30 λ for slower (e.g. silt/clay –like) bottoms

ONR question 3: What instruments are needed to get the geology and geophysics (G & G) data these experiments and modeling efforts will require?

Appendix A (other assets) lists the G & G assets we currently have available. Section IV C lists recommended G&G measurements. However, there are limitations which impede our objectives, such as the ~7-10 m maximum depth for piston coring, questions about ground truth geophysics from vibro-coring and the very significant time required to sample scattering patches at resolutions like 0.2 λ.

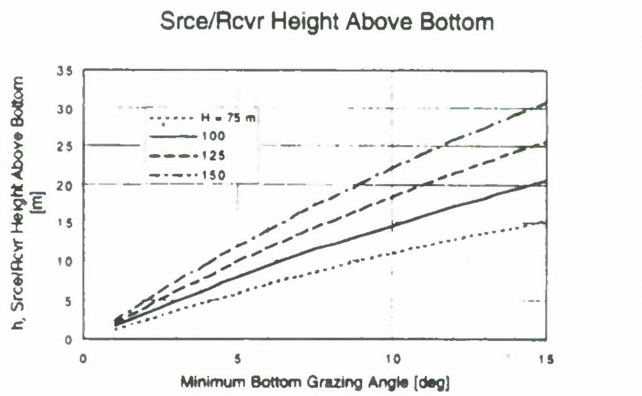
B. Recommendations for Acoustic Measurements:

Measurement Objectives to Address Questions of Section III:

- Measure broadband reverberation and scattering on vertically directional arrays, (VLAs or billboard arrays), where geo-acoustic bottom model is well known. Measurements should resolve interface contributions from sub-bottom layer scattering.
- It is recommended that both direct-path scattering experiments and long-range reverberation experiments be conducted and be measured in the same frequency bands so they can be reconciled to each other.
- A direct path scattering measurement, which estimates the scattering T-matrix, can isolate different scattering mechanisms.
- Minimize multipath and pulse length interference in direct path measurements (see Fig. 5 by Cable, as example) and minimize hybrid path contamination.
- Make broadband (50-6000 Hz) measurements.
- Measure enough ensembles to estimate 2nd order statistics of the fields (e. g. the std. dev., 2-point correlation functions, spatial coherence, Gaussianity or non-Gaussianity, and if possible PDFs / CDFs, so will need estimates of tails in density functions).
- Assessing the relative influence of propagation and scattering fluctuations requires very controlled experiments (e.g., fixed and directional source(s) and receiver(s)).
- Measure a wide range of grazing angles that are well-resolved in grazing angle and include angles above and below critical angles looking for amplitude enhancements and frequency dependence.
- Look for observable elastic/visco-elastic/poro-elastic/shear wave effects in scattering.
- Isolate water sediment interface scattering.
- Isolate sediment sub-bottom horizon interface scattering.
- Measure vertically bistatic scattering and reverberation.
- Use high enough resolution to isolate scattering patches of interest.
- Measurements should be conducted in both daytime and nighttime conditions to study possible contamination of bottom scattering /reverberation from fish and to measure SVP effects on results.

Experiment Design: No Multipath Interference

- Bottom echo arrives at receiver before first surface return



Experiment Design: No Incident Pulse Interference

- Pulse ends before bottom scatter arrives

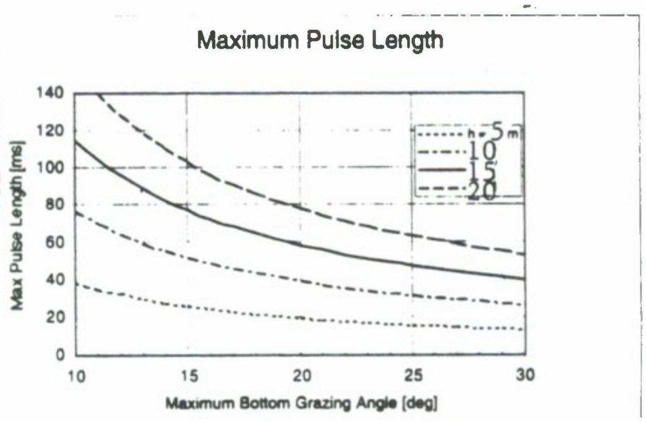


Figure 5. Nomographs to minimize multipath and pulse length interference. Courtesy of P. Cable.

- Measurements should include horizontal directionality, bistatic/multistatic measurements and other attempts (e.g. billboard arrays) to characterize the 3-D nature of the scattered field in range, depth and azimuth.
- Measurements should include 2-4 sites per generic bottom type (can we define geophysical provinces?).
- The patches used for direct path scattering measurements using highly directional arrays should be the same as the patches where high resolution G & G measurements (Section IV C) are taken.

Specific Acoustic Quantities Needing Measurement:

- Local scattering strength vs. incident and scattered angles, and vs. frequency (angular information obtained from VLA array signal processing). (See Fig. 6 from Holland, as a good example of scattering strength extraction.)
- Reverberation (including out of plane to characterize 3-D effects) vs. frequency, time, and angles where possible (angular information implies an inversion and/or VLA array signal processing).
- Bottom loss vs. angle and frequency.
- PDFs and CDFs of reverberation time series.
- Horizontal and vertical spatial coherence of reverberation.
- Transmitted field measurements (source to bottom point(s) and bottom point(s) to receiver.
- Time spreading (vs. range, depth and frequency).

Additional Questions Which Must be Addressed in Reverberation/Scattering Experiments:

- Are bladdered fish and/or other biologic organisms containing near resonant bubbles present, which could distort bottom scattering and reverberation measurements?
- What is the contribution of scattering from the sea-surface interface and near-surface bubbles to the reverberation data?
- Is entrapped gas present in the bottom sediment?

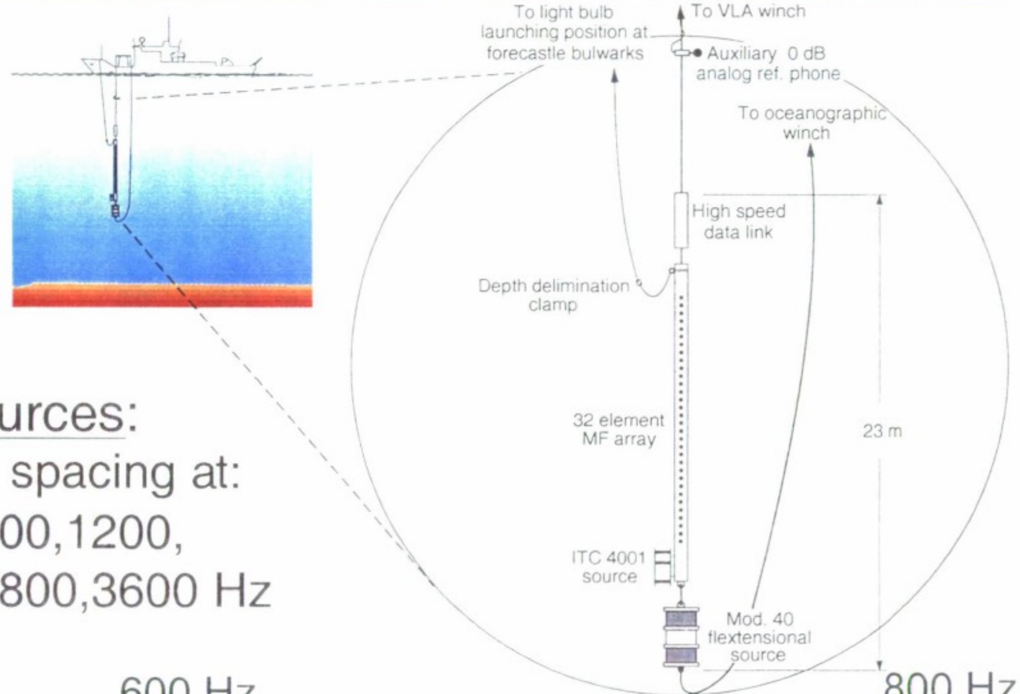
The lists above do not include standard ancillary environmental measurements such as CTDs, wind/wave measures, internal wave measurements, currents, satellite data, etc., but we need a good oceanographic characterization of the water column and sea-surface while the experiments are being conducted. Ideally, this should mean help from physical oceanographers.

C. Recommendations for Geology and Geophysics Measurements:

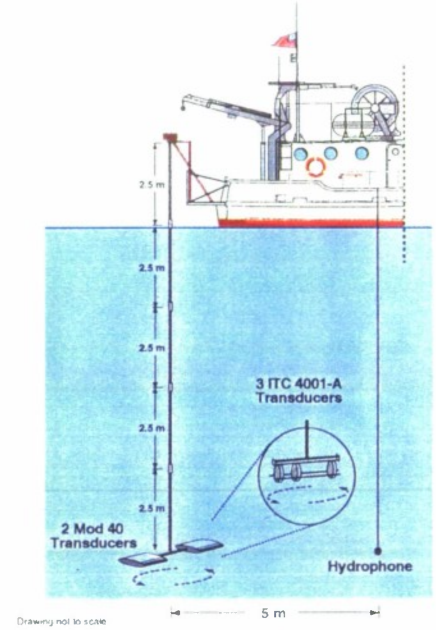
To support the acoustic measurements, localized high-resolution G & G measurements are needed – including density, compressional and shear speeds and attenuations and their gradients vs. depth. (Note: These may require some inversion procedure from high frequency sonar data). In slow bottoms researchers may need to measure down to as much as ~30 λ deep; while in fast bottoms, measurements down to a few λ deep will suffice.

Direct Path Technique

and calibration



source calibration



Sources:
λ/2 spacing at:
600,1200,
1800,3600 Hz

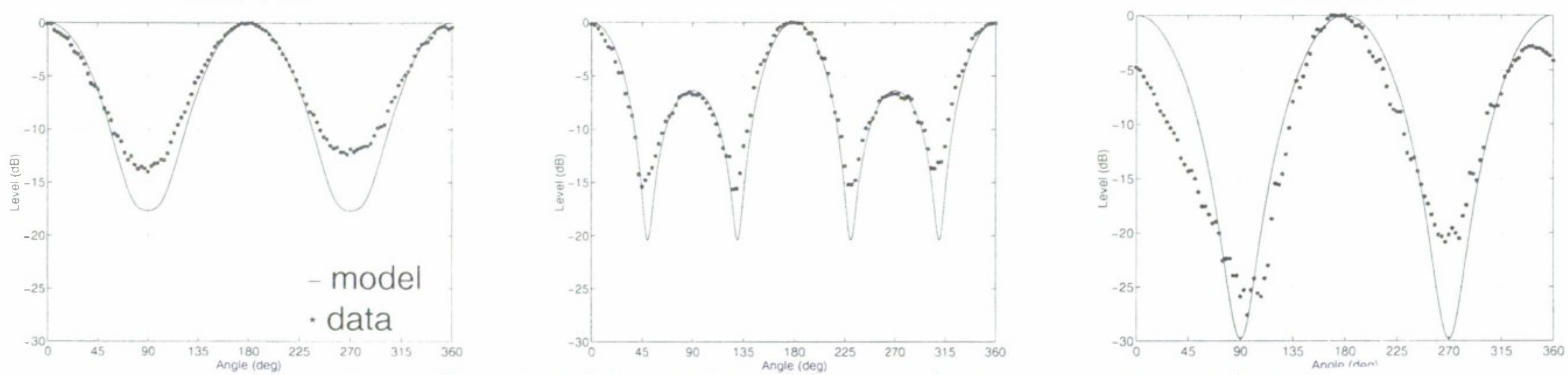


Figure 6. Illustration of direct path scattering strength measurement system using VLA and near bottom sources. Courtesy of C. Holland.

Specific Geological and Geophysical Quantities Needing Measurement:

- Density, shear strength, grain sizes and material type vs. depth via piston corer.
- Compressional speed c_p, density ρ, and attenuation α vs. depth (via Holland's time-frequency techniques to measure reflection loss and invert).
- 3-D spectra of density, compressional speed and α(via hi-resolution chirp sonars, pseudo-spectral technique and tomography (Turgut (1997), Yamamoto (1996))).
- Porosity (Stoll (1986), Tang (1999) and Yamamoto and Turgut (1988)).
- Gas pocket indication (via chirp sonar).
- Water-bottom interface roughness spectra (use 2-D swath systems. For high resolution, use stereo-photogrammetry – Briggs (1991), Lyons (1998), or laser – Jaffe (1996)).
- Basement interface roughness – (No known high-resolution techniques to measure this).

For Water-bottom interface:
- Need high-resolution bathymetry and roughness:
- Use multi-beam Swath systems.
- Use stereo photography (in small patches).
- Try new time reversal techniques outlined in Rose et. al., (1999).

For Sub-bottom structure:
- Use chirp sonar for layers (0.1 m – 1 m resolution) which can also identify gas presence.
- Use a Uniboom/Sparker (digitized reflection loss estimation) for layer structure.
- Take piston cores (up to 7-10 m depth) – do some ~ 1 m apart - gives shear modulus, grain size, density and material type.
- Use Holland's (Holland (2000)) time frequency technique- (good to depth = water depth-15m).

D. Typical Requirements for a Specific Experiment:

- Select a maximum of 5 hypotheses/questions to test.
- Start simply – choose homogeneous, flat areas at first
- Identify all necessary measurement assets for these tests and how they match with ships available.
- Layout a 2 - 3 week time line for measurements and add in weather days and transits and equipment shakedowns.
- Select 2 or 3 sites within an experiment area.
- Layout specific measurements for each hypothesis test set and time required. (Allow for sharing of ancillary data collection efforts).

E. Site Criteria:

Choose sites to fit specific scientific questions such as some of those listed in Section III above. In general desirable sites have:

- Water depths from ~70 – 200 m.
- Low fish scattering.
- Low sea states.
- Low shipping noise contribution.
- Benign acoustic propagation conditions (e.g. ~ iso-velocity sound speed profile).
- Flat Bottom (<0.1° slope) (to start with).
- Homogeneous bottom types (initially).
- Different bottom types (e.g. sand, silt, clay, rocky, etc.). Ideally an experiment area should have more than one of these locally homogeneous types in the same general area.
- Minimal oceanographic water column complications, i.e. minimal internal wave effects, no fronts, no eddies, and minimal tides.
- Sites should be well characterized from a G & G point of view.

Sites with some known G & G, reverberation, and scattering data that could prove useful and scientific points of contact are:

- Site FOXTROT - Southeast of Hudson Canyon off Long Island (B. Cole at PSI).
- Capraia Basin near Elba in the Mediterranean (Ellis at DREA, Holland at SACLANTCEN).
- Timor Sea (Gauss at NRL B. Cole at PSI)
- Littoral Warfare Advanced Development (LWAD) site off S. Carolina (F. Erskine at NRL).
- Scotian Shelf (Hines at DREA and Gauss at NRL).
- LWAD site on west Florida shelf (F. Erskine at NRL).
- China Sea, especially East China Sea (Zhou at Ga. Tech.). Figures 7 and 8 show the overall area and detailed area charts for the planned U. S. Asia Experiment. (note: East China Sea is mostly sand over rock).
- Sea of Japan (Turgut at NRL).
- SW approaches to the UK (Ellis at DREA and Gauss at NRL).
- Malta Plateau (Holland at SACLANTCEN and Preston at ARL/PSU).

F. Equipment Recommendations for Acoustic Measurements:

(All equipment calibrated)

- Vertical line array (VLA) and horizontal line array (HLA) receivers need:
  - Wide dynamic range
  - Narrow beamwidths
  - Broadband capability

- VLA sources should be:
  - Steerable
  - Shadeable

Location

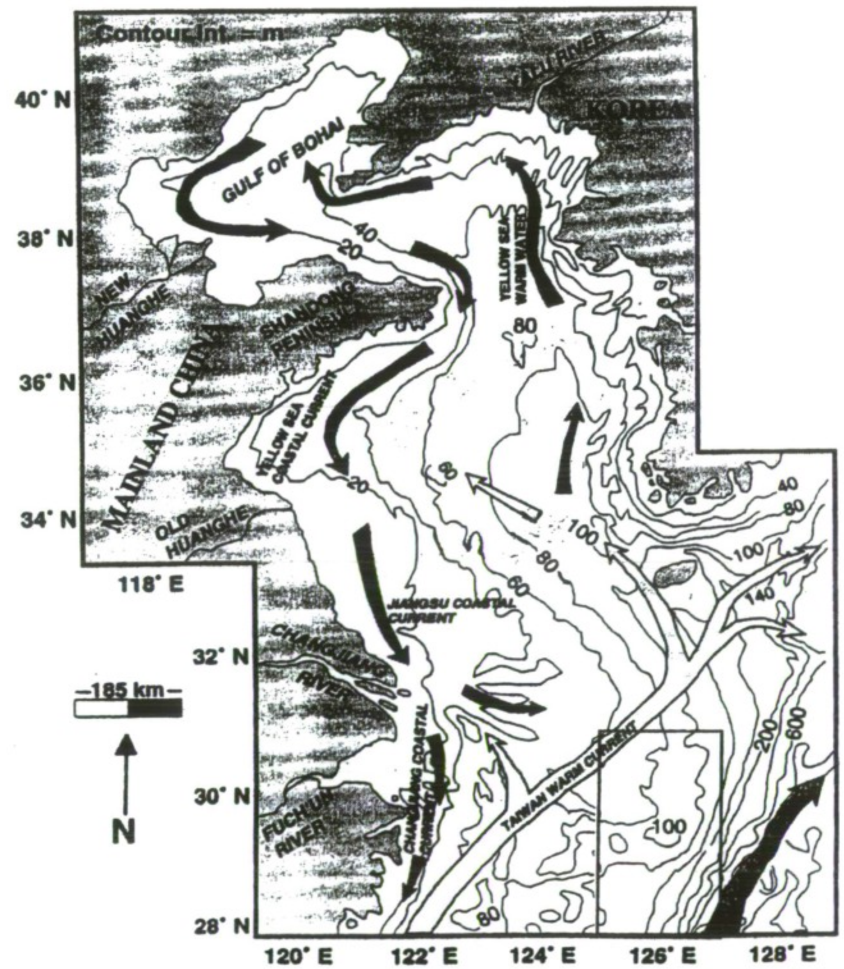


Figure 7. General area chart for East China Sea showing proposed US Asia experiment location in box at lower right. Courtesy of Chiu and Denner.

Bathymetry

234 Z.X. Liu et al. / Marine Geology 145 (1998) 225-253

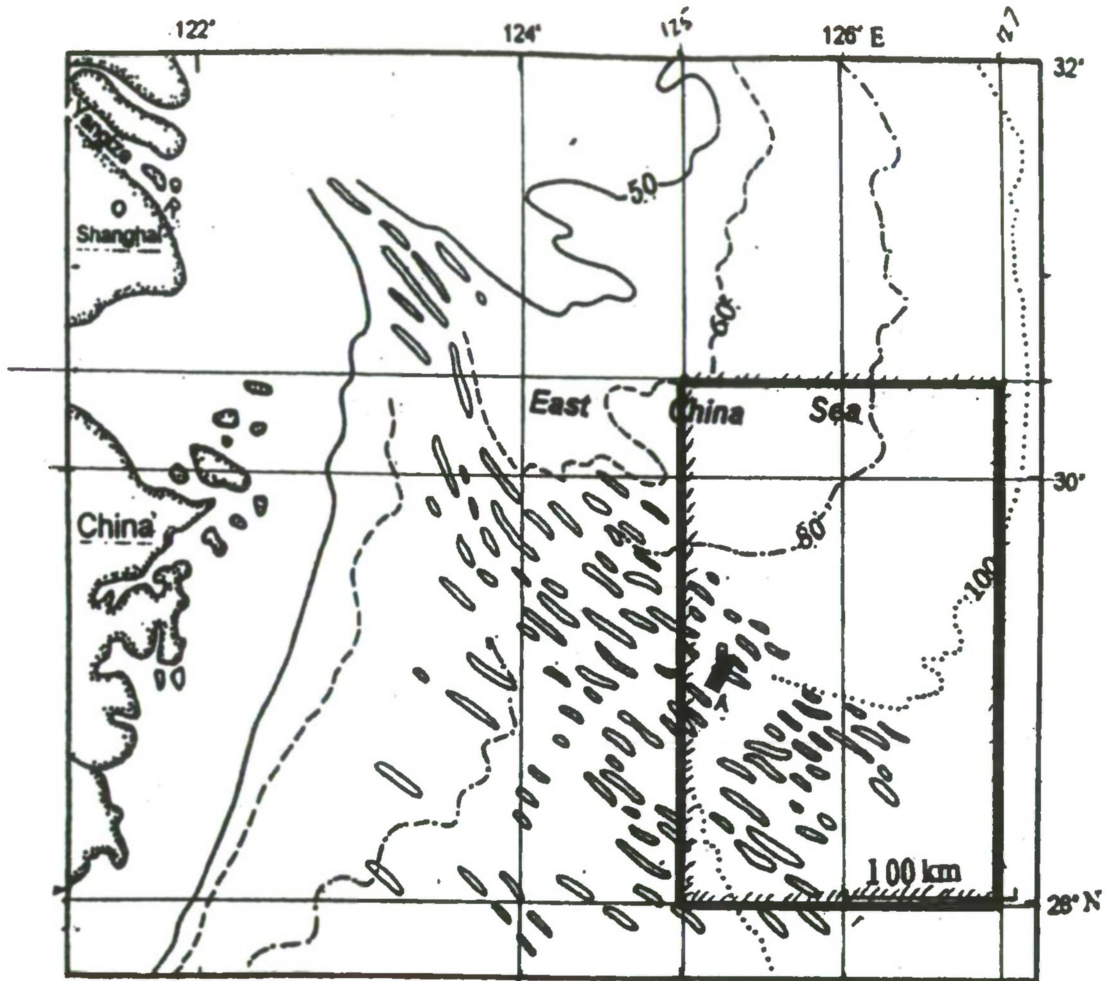


Fig. 7. Moribund tidal sand ridges in the East China Sea formed at the time of lower sea level. Interpreted from 1 : 2,000,000 sea-bottom topographic map of the East China Sea, with water depth contours in metres, by MGMR, China. Location in Fig. 1. From Yang and Sun, 1988. *A–B* represents the position of the sparker profile of Fig. 8.

Figure 8. Detailed bathymetry chart for East China Sea showing proposed US Asia experiment location in box at lower right. Courtesy of Chiu and Denner.

Have adequate SL for scattering measurements
Have high source level for reverberation measurements
Have broadband capability

- Use both coherent sources (CWs, LFMs etc.) and impulsive sources: (SUS, Lightbulbs)
- Calibrated echo repeater
- Ocean Bottom Seismometer (OBS) (<200 Hz only)
- Other calibrated targets (NUWC, BBN reflectors)

G. Generic Acoustic Measurement Geometries:

See Figs. 9 and 10 as possible examples.

H. Miscellaneous Ship Time Estimates:

- Holland – 4 cores plus reflection loss measurement plus 1 direct path scattering experiment requires 2 ship days (Holland (2000)).
- Turgut – Chirp sonar mapping of 5 km x 5 km x 30 m volume requires 1 ship day.
- Bottom Stereo-photography – for now, this is a very localized measurement (Lyons still needs a pressure housing for shallow-water bottom depths we deal with typically, Lyons (1999)).

I. Other Useful Measurements:

- Identify experiments of opportunity for specific hypothesis testing (e.g. Littoral Warfare Advanced Development (LWAD) program).
- Use ancillary tank measurements.
- Use ancillary lake measurements.

V. SUMMARY OF THE WORKING GROUP FINDINGS - MODELING

A. Future Modeling Work (primarily reverberation modeling)

Background

There are a variety of theoretical expositions and models of physics-based bottom scattering (e.g. Mourad-Jackson (1993), Ivakin (1986, 98), Hines (1990), Makris (1998), Thorne-Pace (1983), Yamamoto (1996), Cable (1997), Essen (1994), Wurmser (1996), Holland (1998)). For the most part they are untested in the LF and MF range against shallow-water data. There is a paucity of scattering data - particularly data sets complete enough to test against scattering models (a check of some references, such as D. McCammon's (1991) review of available data, shows it is a pretty slim list). There exist some "research strength" ray-based or normal mode models of reverberation such as Ellis' OGOPOGO model (Ellis (1995)), but typically these reverberation models use Lambert-

Generic Experiment Geometries

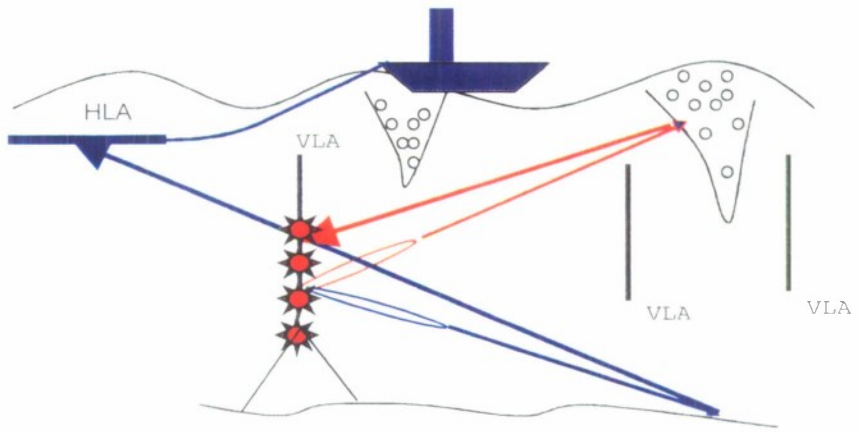


Figure 9. Fixed directional source, one or more bistatic VLA receivers(fixed or drifting) and towed HLA

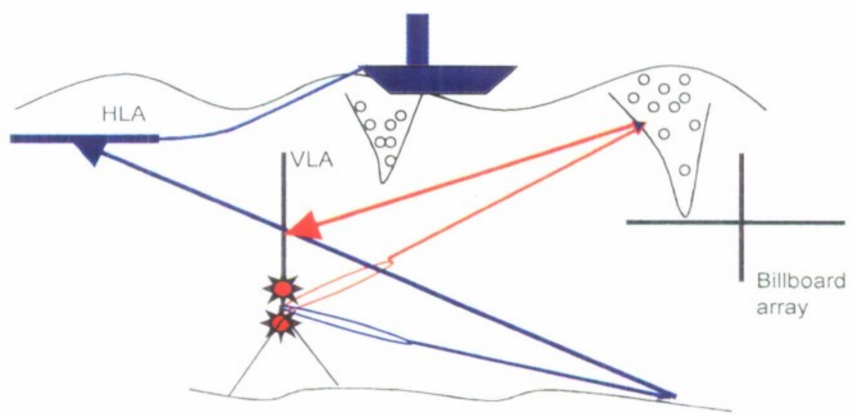


Figure 10. Fixed VLA receiver with (e.g. 2 element) directional source, one or more bistatic billboard or VLA receivers (fixed or drifting) and towed HLA

like descriptions of the interface scattering physics (which is not really a physics description at all). Thus, the reverb models should be "upgraded" to include enough physics to be able to compare with upcoming ONR measurements (such as ASIAEX).

One related point is that data processing often assumes that direct path scattering is plane wave in nature (e.g. array beamforming) which may be untrue. This could potentially distort model data comparisons. A related issue is whether or not a model makes plane wave assumptions that may not be justified.

Near term

Reverberation models:
- Include the ability to estimate spatial correlation and temporal coherence.
- Improve the N by 2-D PE reverberation models. For example, the UMPE-Reverb model, by Smith, Tappert and Hodgkiss (1993,1996) should add the ability to handle sediment volume scattering and extend the region of validity via testing. For the OGOPOGO model, continue the validation of new empirical volume scattering capability. Figure 11 is a sample volume scattering prediction from Ellis.
- Develop better G & G interpretive models (perhaps Buckingham's new work can help here Buckingham (1999)).

Scattering models:
- Develop and refine the estimation of the scattering T-matrix (See Fig. 12 for an example from Tang).
- Improve/add ability to model discrete scatterers.
- Add capability to do broadband scattering estimation (Which models?)
- Continue validation efforts for NRL's small slope improvements to rough interface scattering theory (see Fig. 13 for an example).

Long term

For reverberation and scattering models:
- Improve coupled mode models (Evans'(1983), Odom's (1996), Knobles'(1994, 2000) e.g. add 3-D and broadband capability, increase speed. See Fig. 14 for example from Odom's Coupled mode model
- Improve Finite Element, Finite Difference, and Pseudo Spectral models.
- Develop reverberation and scattering benchmarks accepted by the scientific community. (The ASA penetrable wedge problem has acceptable outgoing solutions but has the incoming solution been agreed on?) We need more benchmarks. Jensen, Ferla and Gerstof (1995) have published some solutions from the May 1994 reverberation and scattering workshop.
- Need physics based models to estimate statistics of reverberation and to estimate G & G parameters.

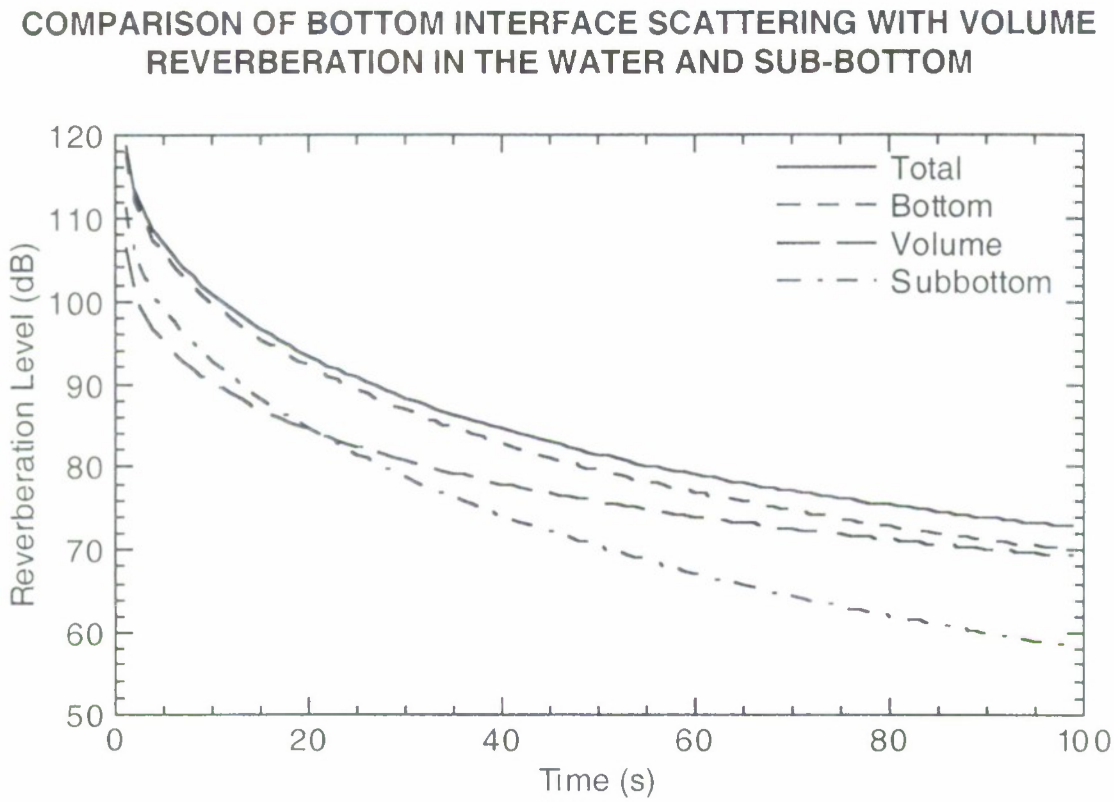


Figure 11. Example of reverberation predictions from DREA OGOPOGO reverberation model. The figure compares the time dependence of (i) volume reverberation in the water column (long dashes) and (ii) volume reverberation in the sub-bottom (dash-dot), with (iii) bottom boundary reverberation (short dashes). The solid line is the sum of the three components. Courtesy of Ellis et. al. (1997).

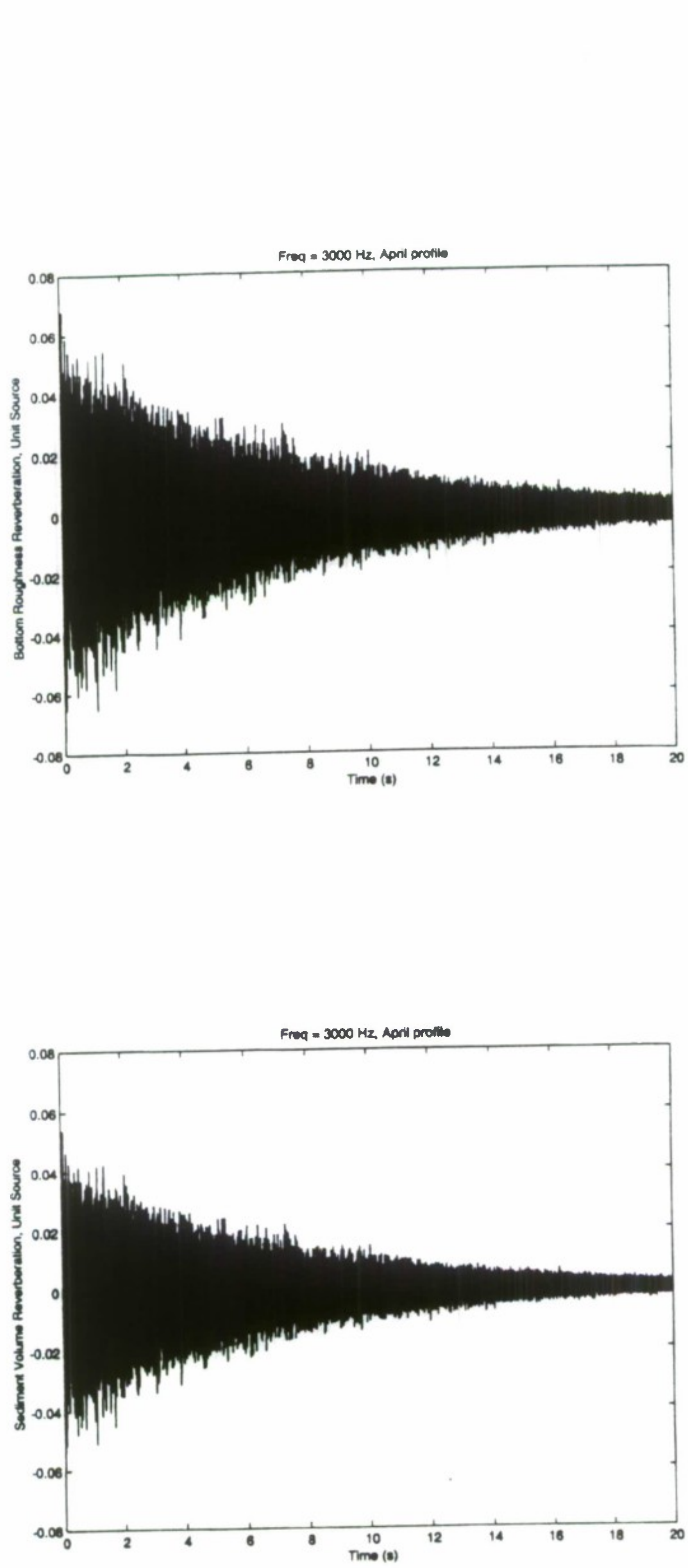


Figure 12. Predicted broadband time series from interface backscatter (top) and from sediment volume backscatter (bottom) using the T-matrix model which can separately predict each of these effects. Courtesy of D. J. Tang.

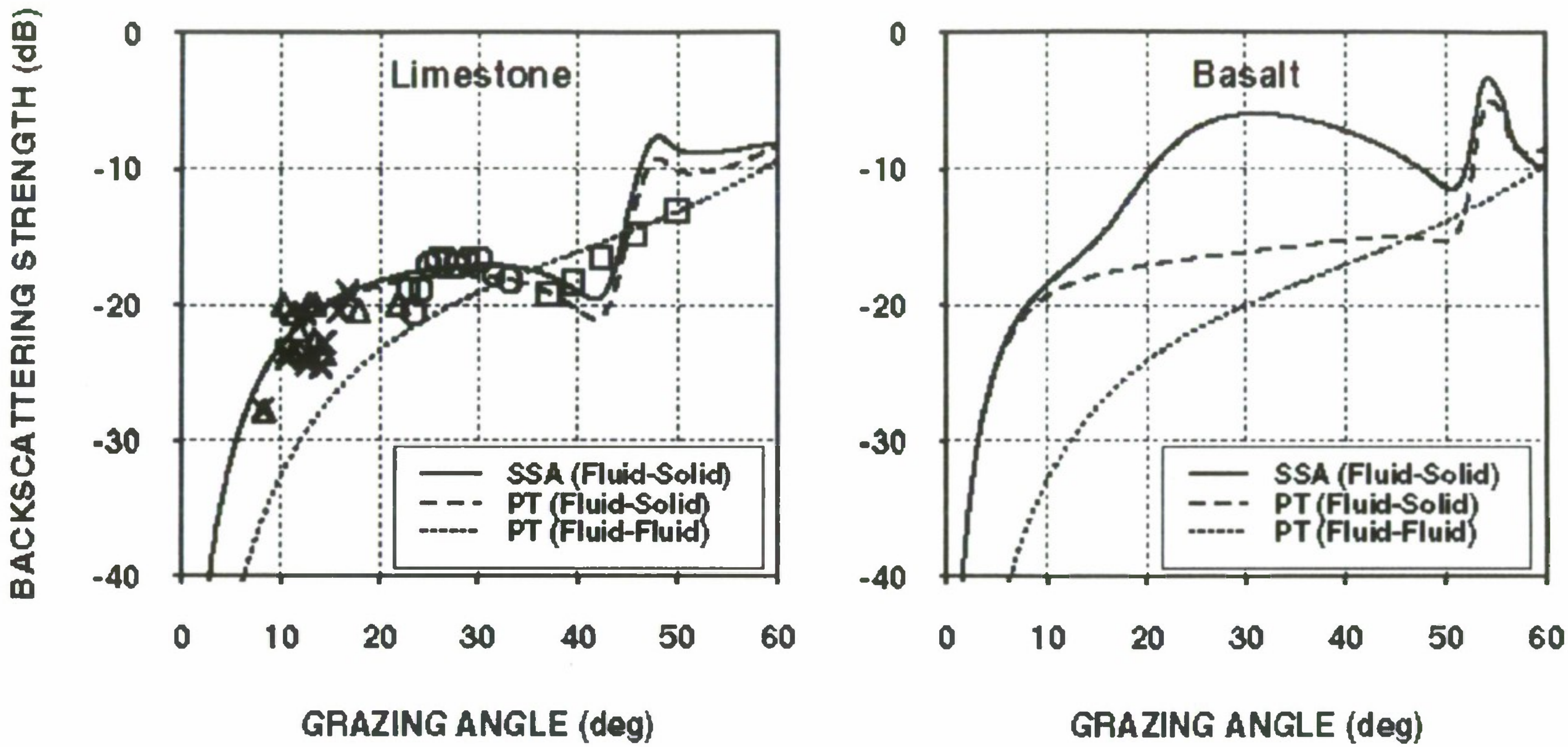
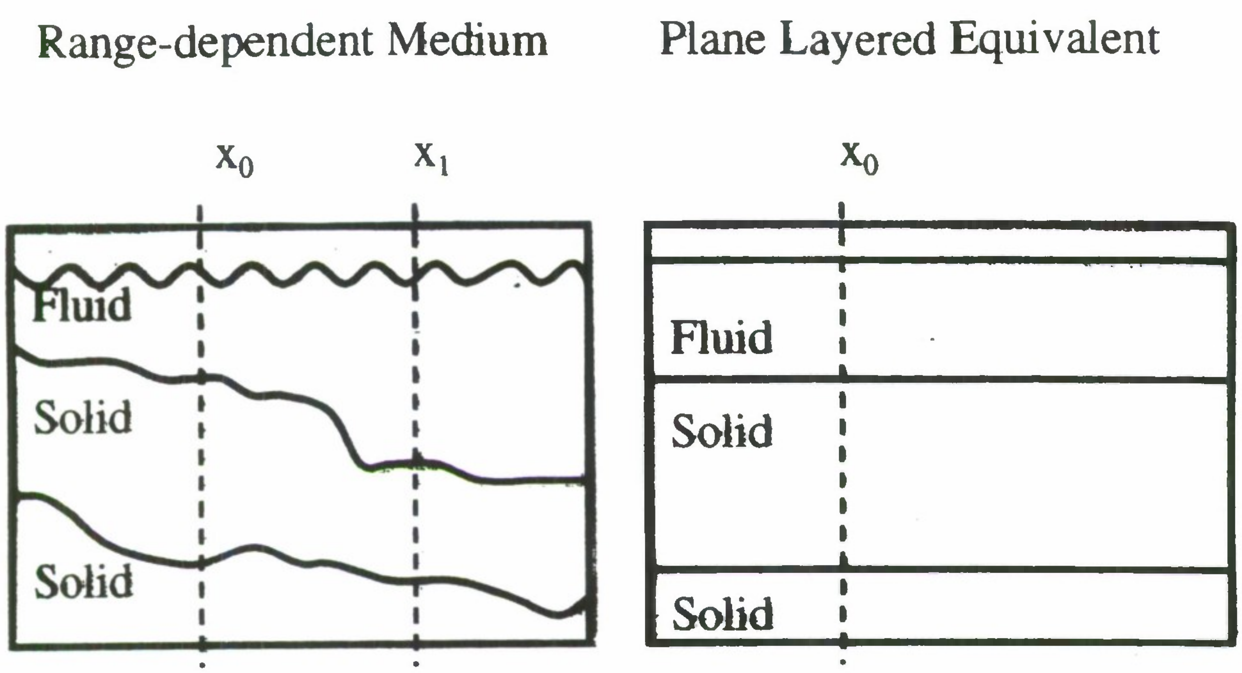


Figure 13. Application of interface-scattering models to limestone and basalt bottoms at 3000 Hz, illustrating the importance of correctly modeling elastic effects. Each plot compares a prediction using the small-slope approximation (SSA) of Wurmser (NRL) to first-order perturbation theory (PT) predictions for both fluid-solid and fluid-fluid boundary conditions. The plot on the left includes a data-model comparison for an exposed limestone shallow-water site off North Carolina. The acoustic data (symbols) were collected monostatically by Soukup (NRL) using an omnidirectional source and a vertical-line array receiver during LWAD FTE 96-2 (site Q: □,O) and LWAD SCV-97 (site SR2: **X**,Δ). Courtesy of R. Gauss.

Application of Local Coupled Mode Theory



We compute local modes from the local plane layered model and use them to express the wavefield of the range-dependent model at x_0. The plane layered model is the local equivalent of the range-dependent model at x_0.

$$\bar{u}(x,z) = \sum_r c_r(x) \exp\left(-i \int_0^x k^r(\xi) d\xi \right) \bar{u}^r(z;x)$$

Figure 14. Illustration of use of local coupled mode theory to predict range dependent scattered fields. Courtesy of R. Odom.

B. Results from the Swam 99 Workshop Hosted by K. Smith and A. Tolstoy

Two weeks after the reverberation focus workshop, a Shallow-Water Modeling Workshop (SWAM99) was held in Monterey, CA (see Ref. in Section VII) to compare selected one-way range-dependent solutions among various scientists using their favorite codes to estimate TL. With no apriori knowledge of grid sizes, interpolation schemes or output averaging each scientist ran various cases using his or her own/favorite model. These model runs were compared for the first time at the meeting. There were differences in one-way TL over certain range intervals among the different answers. For monostatic modeling, this translates into double the TL errors for reverberation estimates. The general trend of the different TL results vs. range was in better agreement so incoherent reverberation estimates may not be seriously impacted, but the issue of how to minimize TL estimation errors in these range dependent environments is not yet resolved.

The implications for our work are obvious – Transmission-loss modeling errors in range-dependent environments could affect scattering parameter estimates that use these models if those kinds of differences are left unresolved.

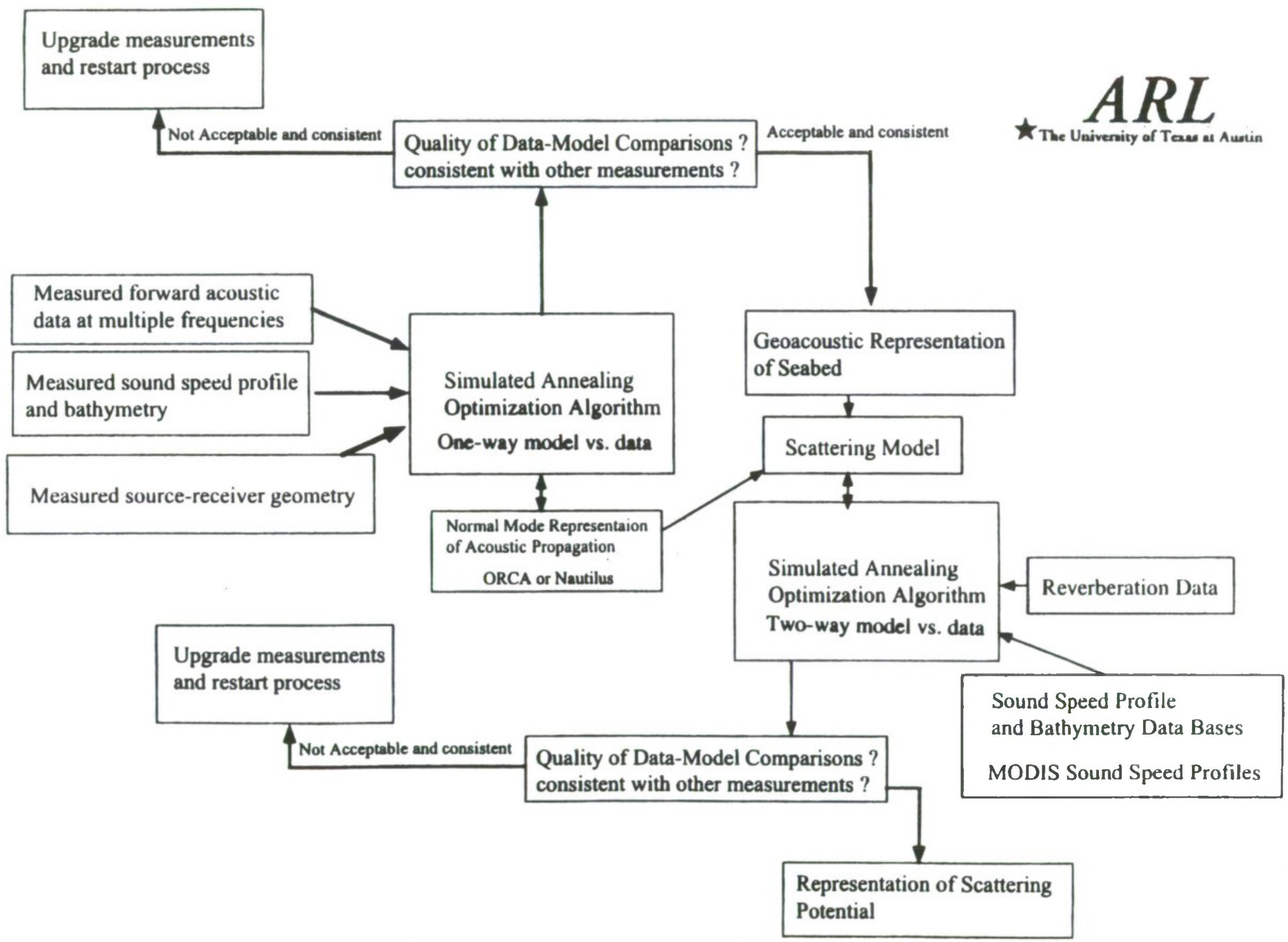
C. Inversion Issues

Inverse techniques are an important part of reverberation data analysis. A good example of a generic procedure to extract scattering and bottom parameters from measurements is given in Fig. 15 from Knobles. Also from Knobles, is Table I, showing how parameters extracted from Yellow Sea data using simulated annealing compare with experimental data from three different sources for the same basin.

ONR Question 4: What tools (including models) are needed to improve the geo-acoustic inversions?

We answer that question with more questions (i.e. research topics):

1. How can we parameterize the inverse problem? For instance we can: a) use a model with n horizontal layers and m parameters per layer; b) use a continuous random media model like Odom's; or c) develop a new approach. If we assume too many parameters the inverse problem may not be tractable; if we assume too few it may miss critical physics in the data.
2. What class of optimization techniques can best be applied to the inversion of propagation and reverberation data to obtain these bottom parameters? (e.g. Genetic Algorithm, Simulated Annealing, etc.). How can we estimate variances in the answers?
3. Given optimization routines and a geoacoustic model, what data and how much data are required for proper validation of a technique?
4. In light of the SWAM99 results – what problems remain with our forward models in range dependent environments?



Approach to Extraction of Scattering Parameters

Figure 15. One approach to inversion of reverberation and TL data for geo-acoustic parameters. Courtesy of D. Knobles.

Table 1. Geoacoustic Models of Yellow Sea Basin

Cloy, Bucca, Fulford, Gomes Geophysical Model bottom water velocity 1500 m/s

37 30 N 125 20 E

Depth(m)	Vp(m/s)	alpha (dB/m-kHz)	rho (g/cc)
0	1650(R=1.1)	.35	1.80
10	1673	.33	1.80
50	1721	.30	1.80
50	5100	.03	2.65

Zhou, Zhang, Rogers JASA 78 1003-1010 (1987).

Depth(m)	Vp(m/s)	alpha (dB/m-kHz)	rho (g/cc)
0	1555	.34*f**1.84	---
10	1610	.33	---
10	1610	---	---

Dahl, Eggen, Tang, Spindel (China-US 1996 experiment) 37 N 124 E

Depth(m)	Vp(m/s)	alpha (dB/m-kHz)	rho (g/cc)
0	1555(R=1.056)	.129	---
2	1555	.129	---
2	1700	.041	---

Knobles (Geoacoustic Model Obtained From Simulated Annealing using HEP data) 34 30 N 124 30 E

				Frequency Exponent
0.0	1644.7(R=1.099)	0.892	1.52	1.996
5.96	1650.36	0.939	1.52	1.996
5.96	1725.29	.474	1.37	1.3
131.85	1848.89	6.17	1.37	1.3
131.85	3000.0	0.02	2.5	1.0

The use of inverse techniques is fundamental to current understanding of our data. Two examples of this are shown as Fig. 16 from Holland showing some of the steps in his time frequency technique to get compressional speed, attenuation, and density from broadband bottom reflection data. A second example, Fig. 17, from Turgut shows estimated compressional and shear speeds and density for a 34m X 600 m, 2-D slice of the bottom using his Biot-based chirp sonar inversion technique.

VI. WORKSHOP SUMMARY

The questions listed in Section III represent the key scientific issues regarding shallow-water bottom reverberation measurements, local scattering measurements and modeling of both processes.

Sections IV B and C summarize recommended measurements needed to address the questions of Section III.

Sections IV A and V B attempt to answer the four questions listed in the introduction that were posed by ONR during the workshop. On the question of equipment, the sense of the meeting was that much more is needed in the way of usable G & G tools but no specific new equipment items were put forth. On the question of inverse methodologies four areas of investigation were suggested as next steps in Section V.

More realistic community-accepted reverberation and scattering benchmarks are needed for modelers and other analysts.

A solid scientific foundation is needed to extend the local scattering measurements to predict longer-range (multipath dominated) shallow water reverberation. To accomplish this, wide area assessment techniques like EAST and REA will need improvement and validation.

For fine scale measurements and analysis, geo-acoustic parameters are ideally needed down to 30 λ in depth at 0.2 λ resolution in both depth and area over selected patches. At 5 kHz this means 6 cm resolution. The resolution requirement currently seems beyond our G & G measurement capability implying stochastic extrapolation techniques will probably be necessary.

The need for multidisciplinary experimental efforts with acousticians and geophysicists in particular was deemed key to future efforts to advance our understanding in this area.

Hi-Res Geoacoustic Inversion

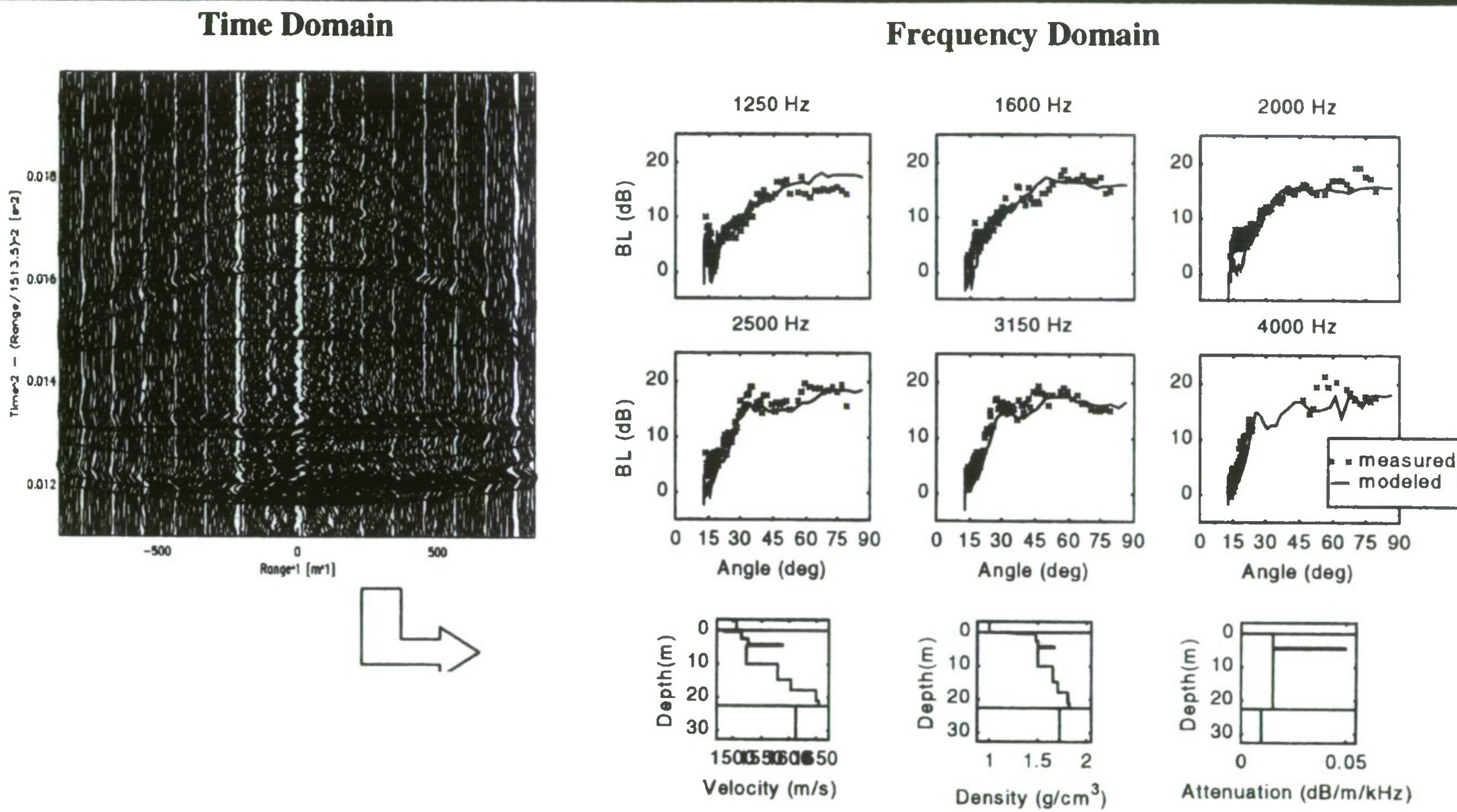


Figure 16. Example of inversion of bottom reflection data for compressional speed, density and attenuation vs. depth. Courtesy of C. Holland.

Chirp sonar bottom inversion at AMCOR-6010 site

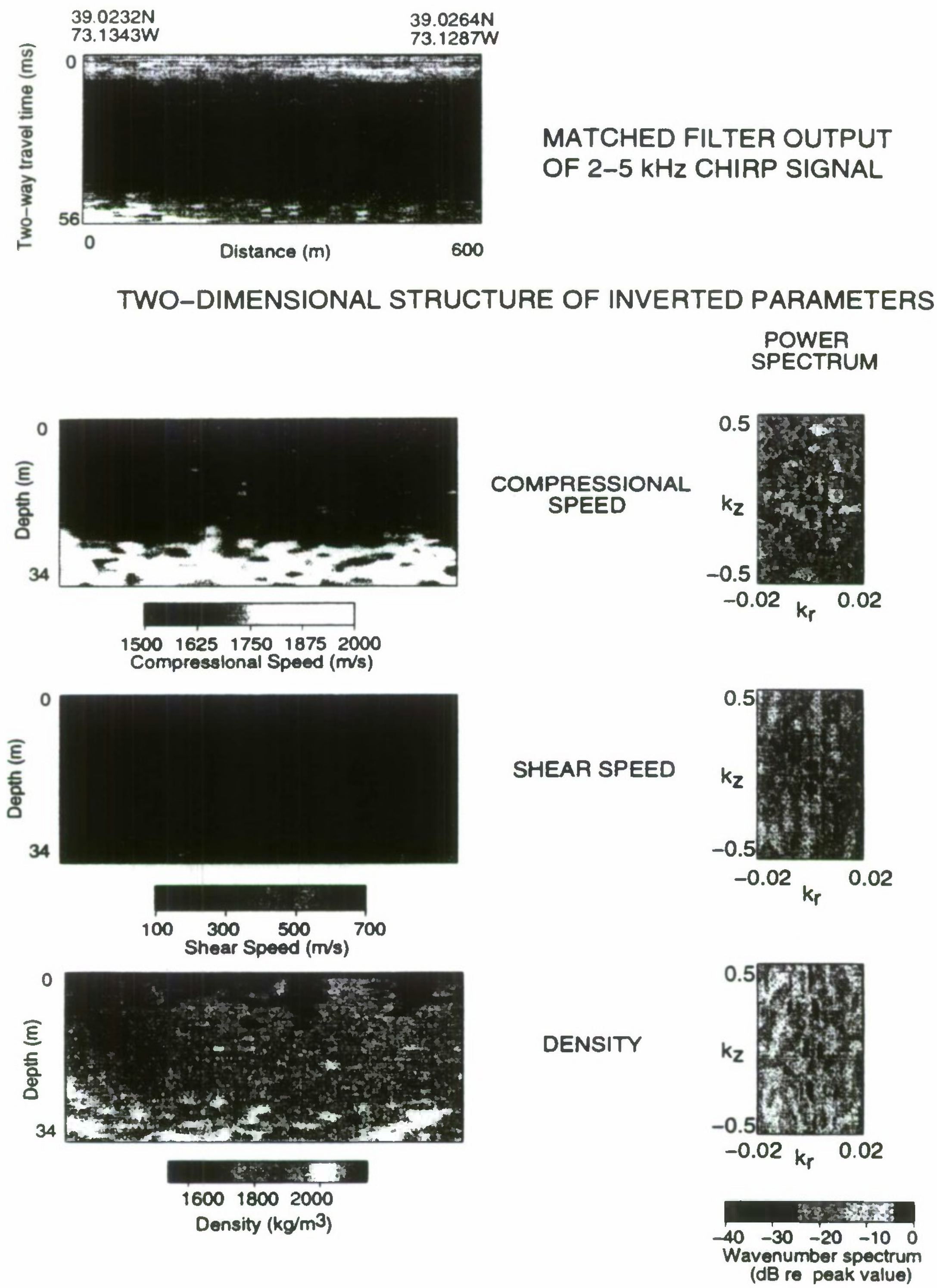


Figure 17. Example of inversion of chirp sonar data for compressional speed, density and shear speed vs. range and depth. Courtesy of A. Turgut.

VII. OTHER RELEVANT WORKSHOPS:

The following workshop results were particularly helpful to this workshop and served as a starting point for our discussions.

Report on the Office of Naval Research Shallow-Water Acoustic Workshop, J.F. Lynch, Rpt. WHOI–97-12, October 1996.

Report on the Office of Naval Research High-Frequency Acoustic Workshop, E. I. Thorsos, Rpt. APL/UW-TR-9702, April 1996.

Toward Developing Hypothesis and Tests of the Dominant Bottom Interaction Mechanisms, R. Gauss NRL, Washington DC, August 1995.

Interactions between Environmental Processes at the Seabed and High Frequency Acoustics, D. R. Jackson and P. A. Jumars, APL/UW, March 1992.

SWAM99 workshop Sept 1999, Monterey CA – Book in preparation for 2000,
See http://web.nps.navy.mil/~kbsmith/swam99.htmlfor more information in the interim.

US – Asia experiments:
Report on the Office of Naval Research Phase II International Workshop on Shallow Water Acoustics, Seattle, June 27, 1998, C. Chiu and W. Denner, Rpt. NPS-OC-98-005PR, Sept 1998.

See also http://arl.nus.edu.sg/asia for a list of reports, workshops and bibliography.

APPENDIX A. AVAILABLE ASSETS

<u>Research Sources:</u>

Vertical Line Array (VLA) sources:
Mid-Frequency (MF) MPL-Scripps 29 element (3 - 4 kHz)
Low-Frequency (LF) MPL-Scripps (low source levels (~180 dB /chan))
MF/LF TVDS NUWC (0.6 - 4 kHz)
LF array of XF-4s with CST beamformer ONR (0.35 - 1 kHz)
MF/LF – SACLANTCEN (0.3 – 1.5 kHz)

Mini VLAs:
MF – SACLANTCEN (3 - 4 kHz)
Barrel stave DREA

Billboard: RSMAS – Univ. of Miami (0.1 –3.2 kHz)
Parametric: DREA, SACLANTCEN (1 - 10 kHz)
Sparkers: ARL/UT, SACLANTCEN
Misc.: NRL/LWAD (0.35 - 5 kHz), China, LBVDS, SACLANTCEN's BB source
Other impulsive sources: SUS and lightbulbs

<u>Non-Research Sources</u>:

Hull-mounted sonars: Selective beam level data available to the research community with certain source levels and bandwidths, but beamwidths require clearances. Selected and restricted element level data may be available but with more effort.

<u>Research receivers:</u>

VLAs:
Mid-Frequency (MF) MPL-Scripps 29 element (3 - 4 kHz)
DUSS – MF (64 chan, 24 bit) SACLANTCEN
SWAMI, LF (32 chan) ARL/UT (10-1000Hz)
Satellite based VLF NRL
SGAMs LF NRL
NRL/LWAD (0.35 - 5 kHz)

Horizontal line arrays (HLAs):
MF Cardioid SACLANTCEN
LF/MF DREA, SACLANTCEN
LF/VLF bottom mounted arrays (various) NRL
SWAMI, LF (32 chan) ARL/UT (10-1000Hz)

Other receivers:

Parametric sonars DREA(Hines), SACLANTCEN
Sonobouys
OBS (<200 Hz)

Non-Research Receivers:

Hull-mounted sonars: Selective beam level data is available to the research community with certain source levels and bandwidths, but beamwidths require clearances. Selected and element level data may be available but with more effort.

Other assets:

Chirp sonar NRL(Turgut), SACLANTCEN
Piston Corer
Gravity Corer SACLANTCEN
Swath systems SACLANTCEN
Tomography probes APL/UW
Conductivity probes for porosity APL/UW (Tang)
CTD chains SACLANTCEN
Thermistor chains
Acoustic Lance University of Hawaii/ONR (Wilkens)
Geoacoustic inversion via chirp sonar NRL (Turgut)
Geoacoustic inversion via bottom loss/move out measurements SACLANTCEN (Holland)
Geoacoustic inversion via sediment tomography Univ. of Miami (Yamamoto)

APPENDIX B. SOME CURRENTLY AVAILABLE MODELS USEFUL FOR REVERBERATION STUDIES (AND ORIGINATORS)

The following is list is a sample of some models that can be used primarily for reverberation but some can also do scattering predictions. The models that are available via ASA's web site for the Ocean Acoustics Library, (OALIB) (see ref. † at end of Appendix F) are the only ones that are truly open to researchers. Many others are either somewhat available or available through the Ocean Acoustic Master Library (OAML) process (see ref. ** at end of Appendix F) after written approval by a navy sponsor as a NAVY Standard module or model. Others are available only at the institution where they were created. None of the models below, except for Evan's COUPLE, are currently available on the OALIB (see last reference). The list is not complete but more models are found in the references of Appendix F. More information about the models listed can also be found in the alphabetic reference list of Appendix F under the originator's name.

<u>Ray Based:</u>
GSM – (Weinberg – NUWC)
BiRASP – (Fromm – NRL)
CASS/GRAB – (Weinberg – NUWC)
China models – (Wu)

<u>Wave Based plus Separable Scattering:</u>
BIKR – (Fromm – NRL)
UMPE- Reverb (Tappert – Univ. of Miami, Smith -NPS)
OGOPOGO, SWAMI – (Ellis – DREA)
PAREQ-Reverb – (Schneider, Jensen – FWG, SACLANTCEN)

<u>Two-Way Wave Based Multiple Scatter:</u>
Coupled Mode (COUPLE – Evans – SAIC, Odom – APL/UW, Knobles – ARL/UT
Integral Equation based – (Thorsos et. al. APL/UW, Fawcett - DREA)
Object coupled in wave-guide, FFP based model – (Makris – MIT)
T-Matrix broadband (Range Independent -Tang – APL/UW)

<u>Numerical Two-Way Wave Based:</u>
Two-way OASES (Schmidt – MIT)
FINDIF – (Stevens - WHOI)
Pseudo spectral approach – (Turgut – NRL)
FOAM, SAFE – (Chin Bing – NRL)

APPENDIX C. AGENDA AND LIST OF ABSTRACTS FOR OFFICE OF NAVAL RESEARCH SHALLOW-WATER REVERBERATION FOCUS WORKSHOP

Workshop introductory and technical talks were presented on day one (Aug. 25).

8:15AM	Ellen Livingston	Introductory Remarks
8:30AM	John Preston	Introductory Remarks
8:45AM	Roger Gauss	Measuring and Modeling Reverberation in Shallow Water – An Overview.
9:30AM	Ji-Xun Zhou	Observations & Challenging Issues in Shallow-Water Reverberation.
10:00AM	Peter Cable	Low Frequency Acoustic Reverberation in Continental Shelf Environments.
10:30AM	All	Discussion and general comments
10:45AM	Break	
11:00AM	Nick Makris	Summary of Bistatic Results from the bottom ARSRP at the Mid-Atlantic Ridge.
11:30AM	Dale Ellis	Shallow-Water Reverberation Activities at DREA.
12:00	Charles Holland	Experimental Methods in Shallow-Water Reverberation.
12:30	Lunch	
1:15PM	D. J. Tang	Shallow -Water Reverberation – Modeling and Measurement Issues.
1:45PM	Michael Sundvik	Matching reverberation using a range independent model.
2:15PM	Robert Odom	Propagation & Scattering in the Shallow-Water Waveguide including an Elastic Bottom.
2:45PM	Altan Turgut	3-D Modeling of Bottom Scattering by Using a Pseudo-spectral Method.
3:15PM	All	Discussion and general comments

3:30PM	Break	
3:45PM	Anatoliy Ivakin	Seabed Volume & Roughness Scattering: Models and Data Analysis.
4:15PM	David Knobles	Inversion of Forward Problems used in the Extraction of Low Frequency Bottom Backscatter in Shallow Water.
4:45PM	Nick Makris	A Unified Model for Reverberation and Scattering from Objects in Shallow Water.
5:15PM	All	Discussion and general comments

Day two (Aug. 26th) was structured as follows:

8:00AM	John Preston	Overview 1995 Bottom interaction panel meeting.
8:15-10:00	All	Shallow water reverberation modeling: Current state of reverberation models Unresolved modeling issues Role of inverse techniques
10:15-12:00	All	Shallow water reverberation measurements: Current state of reverberation measurement techniques Experimental problems & issues Desirable experimental assets & geometries
1 PM	Preston	Overview of salient points from the recent ONR Shallow-Water Workshop, salient points from the High-Frequency Workshop
1:15 PM	Holland	Discussion of JRP with SACLANTCEN
1:30-2 PM	Various	Overview of US-Asia experiment.
2:15-5 PM	All	Parallel sessions: Modeling Working Group (Tang) and Experiment Design Working Group (Gauss)

Day three (Aug. 27th):

8:30-12 Noon	All	Summary presentations and discussions of conclusions and report to ONR

APPENDIX D. ABSTRACTS

Low Frequency Acoustic Reverberation in Continental Shelf Environments

Peter Cable
GTE/BBN Technologies

For many temperate zone coastal areas the remarkable feature of shallow water reverberation is a 10-15 dB decrease of bottom scattering strength in the frequency decade below 1 kHz. The Holocene and Pleistocene sediments that comprise the bottoms in these regions are acoustically fast. Consequently the reverberation at search sonar ranges (tens of kilometers) must result from scattering at or slightly below the sediment-water interface. The evidence supporting these statements will be reviewed and the experimental limitations on performing low frequency bottom scattering strength measurements summarized. The outline of theory to explain observed frequency behavior of low frequency reverberation will be presented and the geoacoustical data needed to specify the scattering delineated.

Shallow-Water Reverberation Activities at DREA

Dale D. Ellis
Paul C. Hines
Defence Research Establishment Atlantic

The presentation will review the current status of shallow-water reverberation and related activities within Canada with particular emphasis paid to DREA (Defence Research Establishment Atlantic). A review of publications will be presented, followed by work in progress, and conclude with some thoughts on the way ahead. DREA has a dedicated research vessel (*CFAV Quest*), a strong transducer group, and a history of obtaining quality acoustic measurements. The talk will focus on our current hardware developments (barrel-stave sources, Wide-Band parametric Sonar, active acoustic target, lightweight arrays, etc.) and modelling capabilities (shallow-water reverberation models, sub-bottom scattering model, theoretical scattering work, etc.). These activities have been in support of our active sonar program for both ship-deployed towed arrays and air-deployed sonobuoys. The hardware is used for both environmental and active-sonar measurements, and the models are used to interpret the measurements as well as to plan and analyze the active-sonar trials. DREA is active in multinational active-sonar exercises. Future plans include a continuation of these trials, as well as involvement in international collaborations in environmental measurements and validation of rapid environmental assessment techniques.

Measuring and Modeling Reverberation in Shallow Water
An Overview

Roger Gauss
Naval Research Laboratory

and John Preston
Applied Research Laboratory, The Penn State Univ.

It is well known that the environment plays an integral role in the performance of any sonar system. In littoral water, the importance of scattering from the boundaries and volume are enhanced; furthermore, boundary-interacting propagation often dominates. An overview of the essential scattering and propagation phenomena shown to affect or predicted to affect active sonar performance in littoral water will be presented. Technical issues to be examined include: the spatial, temporal and spectral characters of bottom, volume and surface reverberation as functions of the boundary conditions and the biologics; statistical clutter characterization; propagation effects on signal spreading and surface loss; and shallow-water propagation modeling. Particular emphasis will be placed on identifying those environmental features that can impact low- and mid-frequency (50 Hz to 10 kHz) sonar performance. Recommendations for enhancing our ability to model and predict the effects of the environment will be discussed.

Experimental Methods in Shallow Water Reverberation

Charles Holland
SACLANT Undersea Research Centre

Sonar performance predictions of reverberation in shallow water rely upon good estimates of the scattering strength and knowledge of the underlying statistics. However, little is understood about bottom scattering in shallow water in the frequency range 400 – 4000 Hz, particularly its dependency upon frequency and its relationship to the physical properties of the seafloor. In order to address these issues, new measurement techniques have been developed to probe the frequency and angular dependency of bottom scattering strength and to explore a possible link between the reverberation statistics and the dominant scattering mechanism. Several experimental techniques will be described, including use of coherent and incoherent sources (lightbulbs). The general experimental approach will also be described which includes auxiliary acoustic and geoacoustic measurements designed to explore the relationship between bottom scattering and the physical properties of the bottom. Measurement results and modeling interpretations for several shallow water sites will be presented.

Seabed Volume and Roughness Scattering: Models and Data Analysis

Anatoliy Ivakin
Andreyev Acoustics Institute

Several models are considered for description of the main mechanisms of seabed scattering, which are due to sediment volume inhomogeneity (continuous or discrete) and interface roughness. Commonly, only measurements of the bottom scattering strength (BSS) are being carried out. Frequency-angular dependencies of BSS are analyzed for various types of sediments (clay, silt, sand) and compared for different scattering mechanisms. It is shown that in many practical cases the difference is very small and thus the scattering mechanisms cannot be distinguished and/or separated using only measurements of BSS. However, such distinguishing is critical for understanding nature of seabed reverberation. A method of separation of volume and roughness scattering is proposed and discussed based on measuring the spatial correlation function of the scattered field. Preliminary estimations for optimal parameters and configuration of an experiment are presented. [Work supported by ONR]

Inversion Of Forward Problem Used In The Extraction Of Low Frequency Bottom Backscattering Strengths In Shallow Water

D. P. Knobles
E. K. Westwood,
and C. S. Penrod
Applied Research Laboratories, Univ. of Texas, Austin

Reliable estimates of bottom backscattering strengths in shallow water must include an accurate knowledge of the two-way acoustic propagation. In shallow water and at low frequencies, the geoacoustic structure of the seabed often plays a critical role in defining the nature of the acoustic propagation. Generally the geoacoustic parameters describing the seabed are not well known. Further, it may not be feasible to measure transmission loss at the frequencies and source-receiver combinations necessary for use in the active sonar equation. This work explores the merit of first inverting for the geoacoustic parameters describing the seabed from a limited set of measured forward acoustic data, and then using this geoacoustic representation to compute the acoustic field as needed for the extraction of the bottom backscattering strength as a function of frequency from reverberation data. It is assumed that the seabed can be represented as two fluid sediment layers over a fluid halfspace. Each sediment layer is represented by a sediment thickness, compressional sound speeds, and attenuations that vary linearly with depth, a depth independent density, and a frequency exponent of the attenuation. The frequency exponent is used to take into account more complex mechanisms associated with elastic media. Simulated annealing is used to obtain estimates of the 14 free parameters representing the sediment layers. A normal mode approach is used as the forward model. Several examples are shown that demonstrate the consistency of the approach and insights into the physics of the scattering mechanisms.

Summary of Bistatic Results from the bottom ARSRP at the Mid-Atlantic Ridge

Nick Makris
Dept. of Ocean Engineering, M.I.T.

High-resolution bistatic images of a typical abyssal hill on the western flank of the Mid-Atlantic Ridge are made with a low-frequency towed-array system operating remotely at _ convergence zone (~33.3 km) standoff. Comparison with modeled images, generated from high resolution supporting bathymetry sampled at 5-m intervals, roughly the wavelength scale, reveals that steep scarps return the strongest echoes because they project the largest area along the acoustic path from the source to receiver. Prominent returns deterministically image scarp morphology when the cross-range resolution footprint of the system runs along the scarp axis. Statistical fluctuations inherent in the scattered field prevent the system from distinguishing smaller-scale anomalies on the scarps, such as canyons and gullies (~100-200 m scale), that would otherwise be resolvable in range, in certain bistatic geometries. The mean bi-azimuthal scattering strength distributions of the two major scarps on the abyssal hill are *identical* and equal to the *constant* −17 dB +/- 8 dB. This suggests that long-range reverberation from prominent geomorphological features of the world's Mid-Ocean Ridges can be adequately modeled as Lambertian with albedo $\pi/10^{1.7}$, given supporting bathymetry sampled with sufficient frequency to resolve the projected area of these features.

Propagation and Scattering in the Shallow Water Waveguide Including an Elastic Bottom

Robert I. Odom
Applied Physics Laboratory, University of Washington

Coupled local modes are used to represent the acoustic field in a range dependent shallow water waveguide. The effects of bottom elasticity including sediment anisotropy are included, and both the forward propagating and reverberant fields are treated. We have incorporated random interface roughness into coupled mode theory and derived approximations for the attenuation due to rough interface scattering within the waveguide. In regions where the waveguide can be modeled as slowly varying in range with superposed interface roughness, the attenuation losses due to scattering exhibit a peak where the horizontal modal wavelength is approximately equal to twice the correlation length scale. This is a kind of Bragg scattering in a random medium. We will briefly discuss theoretical results for the coupled mode problem including elastic effects, and present numerical computations for coupled mode propagation in both deterministic and stochastic shallow water waveguides.

Matching Reverberation Data Using a Range Independent Model

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Reverberation at mid-frequencies (2 to 5 kHz) in shallow water environments can sometimes be well matched using a range independent model. This paper outlines conditions, which appear to be sufficient for reverberation modeling efforts developed in support of real-time bottom parameter extraction techniques. Results comparing a bottom reverberation model to three data sets indicate the need to include various propagation effects in order to properly match the reverberation envelope. Mismatch in results appears to occur where there are range dependent sound speed profiles, the influence of surface reverberation, or range dependent bottom parameters. Results in extracting bottom backscattering strength and bottom loss from Navy sonar systems have been checked against independent acoustic measurements, and found to be in good agreement, when proper precautions are taken to meet the assumptions of the range independent modeling techniques.

Shallow Water Reverberation Model Based on Monte Carlo Simulations

Dajun Tang
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This presentation will be divided into two parts. The first part is on the modeling of low-frequency shallow water reverberation in a range-independent environment. Surface and bottom roughness and sub-bottom heterogeneity will be individually addressed using the first-order perturbation theory and a Monte Carlo simulation technique. Reverberation fields under different conditions will be given. Relative importance of different scattering mechanisms to the reverberant field will be discussed. The second part of the presentation will concentrate on experimental design. To support model/data comparison successfully, environmental parameters as input to models have to be measured. We will recommend an appropriate set of requirements on spatial and temporal resolutions of these parameters. Possible field measurement instruments and techniques will also be discussed.

3-D Modeling Of Bottom Scattering By Using A Pseudospectral Method

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A pseudospectral method is used for 3-D numerical modeling of low-frequency (< 1 kHz) scattering from a seabed with wavelength-scale surface roughness and volume inhomogeneities. Sensitivity of bottom scattering to various seabed geoacoustic and statistical properties is analyzed. Seafloor roughness and bottom volume inhomogeneities are described by 2-D and 3-D spectra of Von Karman type whose input parameters were obtained form chirp sonar measurements during the SWARM95 experiment. The 3-D scattering field is calculated for a point source and a gaussian beam over sandy and muddy bottoms including certain 3-D features such as layer dipping and horizontal anisotropy. Low-grazing angle acoustic reverberation from similar bottoms is also studied as a 2-D problem. Modeling results indicate that scattering is dominated by rough surface for sandy bottoms, and by volume inhomogeneities for muddy bottoms. Accordingly, 3-D anisotropy effects are dominated by surface anisotropic scattering for a sandy bottom, and by volume anisotropic scattering for a muddy bottom.

Observations And Challenging Issues On Shallow-Water Reverberation

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A high-quality database on shallow-water reverberation is critical for understanding the basic physics of reverberation such as sea bottom scattering mechanisms. This understanding is, in turn, essential for theoretically modeling reverberation. Long-range reverberation data with high reverberation/noise ratios, obtained from natural labs with flat bottom, are desirable to characterize the sea bottom reflectivity and sea bottom scattering at small grazing angles. In this report reverberation data in a frequency range of 200Hz-4000Hz, obtained with explosive sources, will be reported. The data include: (1) Reverberation intensity as functions of time (distance), frequency, sediment property and receiver/source depths. (2) Spatial (vertical) cross-correlation of reverberation as functions of time, frequency and separation between hydrophones. (3) Sea bottom scattering strength at small grazing angles and low frequencies. (4) Spatial mode filtering of reverberant field. From these observations, some research issues on shallow-water reverberation will be discussed

Fluctuation Statistics in High-Resolution Reverberation Signals

Yevgeniy Dorfman
GTE/BBN Technologies

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Deviation of reverberation signal statistics away from a Gaussian PDF (a Rayleigh envelope) has a profound effect on sonar performance. As the sonar resolution increases, assessment and modeling of the higher order statistics in the reverberation signals becomes increasingly more important.

Monostatic and bistatic reverberation of highly resolved signals from very rough bottoms observed during the ONR ARSRP-93 experiment were statistically analyzed. Scattering from various bottom footprints at a mean frequency of about 230 Hz was considered, assuming each footprint represents the same rough surface ensemble. The reverberation envelope was found to be strongly non-Rayleigh, with the degree of departure from Rayleigh dependent upon the bistatic and vertical grazing angles.

These rough bottom observations can be explained by adopting a continuous scattering model having a Rayleigh envelope, added to a discrete scattering model (arising from a small number of individual features within the sonar footprint) having a distinctly non-Rayleigh envelope. These models, plus a heuristic mechanism of self-selection within the discrete scattering model, arguably explain the observed angle dependence of the reverberation statistics.

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